REGARDING CAST IRON AND STEEL PIPES

JOHN SHARP

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PREFACE

In the ordinary course of engineering practice some of the most important developments have been the direct result of the introduction of new and improved materials of construction. In this respect mild steel, owing to its high tensile strength, ductility, moderate cost and practically unlimited supply, is perhaps the most conspicuous example, particularly in its application to structural engineering work. The success of steel, however, has sometimes led to its introduction and departures from well-established and successful practice, without a due regard to the particular working conditions under which it was to be employed. The result of this at times has been more or less unsatisfactory; in this respect the employment of steel in the construction of underground pipes and conduits has in some examples been equally disappointing. The author for that reason has had occasion to consider various instances of failure of steel pipes, and the relative merits of cast iron pipes under similar circumstances. The following short treatise may, therefore, be taken as a résumé of his observations on this subject, the details of which he now submits as herein set forth in the hope that they may be of interest to engineers and others more particularly engaged in or

responsible for the success of undertakings in which pipe conduits form an important part.

In considering these different aspects of the subject the author has to acknowledge his indebtedness to the various authorities referred to; also to J. A. Gardner, M.Inst. Met., and Malcolm Brechin, B.Sc., for their valued assistance in reading and checking the subject matter with regard to which they were specially qualified to deal.

CONTENTS

Some Notes and Considerations regarding Cast Iron and Steel Pipes

It has often been asked why the Ancient Romans, so advanced in other matters pertaining to the Arts and Science, should have continued in the still more ancient practice of conveying their water supplies to cities in practically open channels, as contrasted with the modern system of conveying water under pressure by means of pipe. The former practice, however, is not to be wondered at when we know of practically the same methods being employed in this country within the last 300 years, in carrying out the New River Scheme for the Supply of Water into London from the Chadwell Springs. The whole circumstances, during the earlier period, seem now to suggest that such important developments were not so much due to more advanced ideas regarding physical laws, but rather as a result of the more recent discoveries and successful application of new materials of construction.

The material afterwards known as cast iron, which calls for special attention here, was first produced accidentally during the smelting process in furnaces which were already being made larger to meet the growing demands for the forgeable qualities of iron and steel. In the year 1550 we learn of the highly liquid properties of this metal (cast iron) being turned to good account by running it into moulds of

simple form. Again, about fifty years later we have a striking example of the rapid developments in Iron Founding, as cast iron cannon were now being produced up to three tons in weight. The strength and other important properties of this new metal, cast iron, which already had been used in the production of hollow castings, was soon afterwards to be recognised by the more advanced hydraulic engineers of their time, and in the year 1664 (fully another fifty years later) we have evidence of the manufacture and introduction of cast iron pipes for the first time to convey water under pressure.

The following record regarding cast iron pipe is of interest, not only from the historical point of view, but also as evidence of the natural properties of cast iron pipe conduits to resist corrosive action when laid underground for the conveyance and distribution of water under pressure.

Ancient Water Pipes.

"There are still in use at Versailles cast iron pipes dating from 1664 to 1688. The total length of these pipes is fifteen and one half miles. A large proportion are twenty inches in diameter, the remainder being twelve and three-fourth inches. They have been laid in lengths of forty inches and are fastened by means of flanges and bolts. The twenty inch pipes are one and three-eighths inch thick, and the others seven-eighths of an inch. The only repairs still found necessary consist in replacing from time to time the bolts which rust through, but even this amount of attention is seldom required."

Such records seem also to suggest the period from which we can trace the development of our modern pipe system,

by means of which it was possible for engineers to adopt the most direct route for the supply main and also follow the natural undulations of the country through which it passes, whether up hill, down through deep valleys or across river-beds, so long as the course was kept within the limits of the hydraulic gradient of the particular scheme under consideration.

Pipes constructed of wood, clay, earthenware, chameroy, lead, wrought iron, steel, and cast iron, have been adopted with more or less success, depending on the purposes and conditions for which they are employed. Pipes constructed of the latter material (cast iron) are the most extensively used to-day in the carrying out of the more important schemes for the conveyance and distribution of water, gas, and other fluids under pressure. More recently steel has entered into competition with cast iron as a material in the construction of pipe conduits; and it is the relative properties of cast iron and mild steel pipe which shall engage our special attention in the following pages.

Cast iron pipe has been almost exclusively employed since its introduction, now well over 200 years ago, and, generally speaking, it has withstood successfully the severe test of time. *Mild steel pipe,* on the other hand, whether rivetted, welded, or solid drawn, is the product of the last twenty to twenty-five years, and therefore of comparatively recent date. Already, however, even after a few years' service, we know of many independent reports from various parts of the world regarding the early development of serious corrosive action and premature destruction of steel pipes.

It is the writer's intention, therefore, in the following pages, to examine some of the more outstanding chemical

and physical conditions which contribute to the comparative success or failure of either quality of pipe, and which it is the desire of all engineers and other authorities to anticipate in the interest of the communities by whom they are appointed.

PHYSICAL AND CHEMICAL PROPERTIES OF CAST IRON, WROUGHT IRON, AND MILD STEEL.

To appreciate the leading characteristics peculiar to the different kinds of pipes with which we are more immediately concerned, it is necessary, in the first place, to examine the outstanding differences in the composition and corresponding physical properties of the different materials employed in the construction of pipes. Table I. includes the composition and relative proportions of the various elements which characterise the different brands of Scotch Foundry Pig Iron used in foundry practice.

TABLE I.

Composition.	For Foundry Castings.			For Chill Castings.		For Steel Castings.
	No. 1. Pig.	No. 3. Pig.	No. 4. Pig.	Mottled Pig.	White Pig.	Hematite Pig.
Iron, - - - -	91·24	92·33	93·06	94·60	95·55	93·43
Carbon Graphitic, Carbon Combined,	3·50	3·15	2·96	2·50	2·33	3·70
Silicon, - - -	2·40	1·90	1·60	·80	·30	2·60
Sulphur, - - -	·02	·03	·05	·22	·35	·02
Phosphorus, - -	·86	·86	·86	·92	·97	·05
Manganese, - -	2·00	1·71	1·40	·85	·40	·20
	100·02	99·98	99·93	99·89	99·90	100·00

Table II. is also added here to show the differences in the composition of pig iron characteristic of the districts

named, owing to the particular quality of iron ore available for the smelting process in these localities.

TABLE II.

Composition.	English Pig Iron.				American Pig Iron.			
	Clarence.		Skimmingrove.		Ordinary Brands.		Special Strong Brand.	
	No. 3.	No. 4.	No. 3.	No. 4.	From	to	From	to
Iron,	91·805	92·644	91·892	92·424	94·77	93·55	95·89	94·54
Carbon								
Graphitic,	2·91	2·90	3·02	2·97	2·50	2·90	1·50	2·00
Combined,	·38	·30	trace	·19	·35	·45	1·15	1·30
Silicon,	2·70	2·02	2·95	3·35	1·50	2·00	·70	1·20
Sulphur,	·037	·076	·008	·056	·07	·10	·05	·06
Phosphorus,	1·64	1·50	1·53	1·53	·50	·60	·40	·50
Manganese,	·53	·56	·60	·48	·31	·40	·31	·40
	100·	100·	100·	100·	100·	100·	100·	100·
Melting Point,	1200° C.		1200° C.		1100° C.		1200° C.	
Tensile Strength,	8 tons p. sq. in.		9 tons p. sq. in.		5 to 9 tons p. sq. in.		13 to 15 tons p. sq. in.	
Density, C.I.,	7·25							
,, M. Steel,	7·8							

The various qualities of Foundry pig iron here referred to in Tables No. I. and II. are successfully used (by careful mixing) for the production of cast iron pipes in the localities mentioned. The English Cleveland brands, however, are more phosphoric, and therefore more fluid; the castings produced are also more dense and close in the grain, and therefore specially suitable for high pressure hydraulic cylinders, water pipes, etc. And for such purposes these and other English brands have been used along with Scotch pig iron with the most satisfactory results.

Table III. shows the composition of different varieties of steel used in the manufacture of steel pipes, including the American production known as "ingot steel," in which manganese is eliminated as far as possible by a special process, so that the steel may offer greater resistance to the serious corrosive action experienced with steel pipes generally. Two examples of steel are also given in Column IV. from Analysis of the 30-inch diameter Steel Main at Coolgardie, and in Column V. of the 21-inch diameter Steel Main at Perth, Western Australia.

TABLE III.

Composition.	I.		II.		III.	IV.	V.
	Open Hearth Steel.		Wrought Iron.		Ingot Steel.	Coolgardie.	Perth.
						30″ diar. S. Pipe.	21″ diar. S. Pipe.
Iron, - -	99·465	98·915	99·657	97·950	99·92	99·290	99·102
Carbon							
Graphitic,	—	—	—	—	—	—	—
Combined,	·100	·200	·020	·250	·02	·173	·147
Silicon, -	·005	·010	·020	·100	trace	·010	·038
Sulphur, -	·015	·045	·001	·100	·02	·050	·101
Phosphorus, -	·015	·030	·001	·100	trace	·035	trace
Manganese, -	·300	·500	·001	·250	·01	·432	·612
Slag (Oxide of Iron), -	·100	·300	·300	1·250	·03	—	—
	100·	100·	100·	100·	100·	100·	100·
Tensile Strength, -	Tons p. sq. in. 22-29		Tons p. sq. in. 18-22		Tons p. sq. in. 20-22		

In Tables I., II., and III. it will be observed that the elements of which *cast iron*, *wrought iron*, and *mild steel* are composed are the same in each. The essential differences in the properties of these three qualities of iron are

therefore characterised by the variations in the amounts per cent. of these elements, individually and collectively (sometimes referred to as impurities). Wrought iron and mild steel, it will be seen, are very similar in composition and also as regards their physical properties, to be referred to later.

It will here be interesting to note the particular characteristic of each element separately when alloyed with

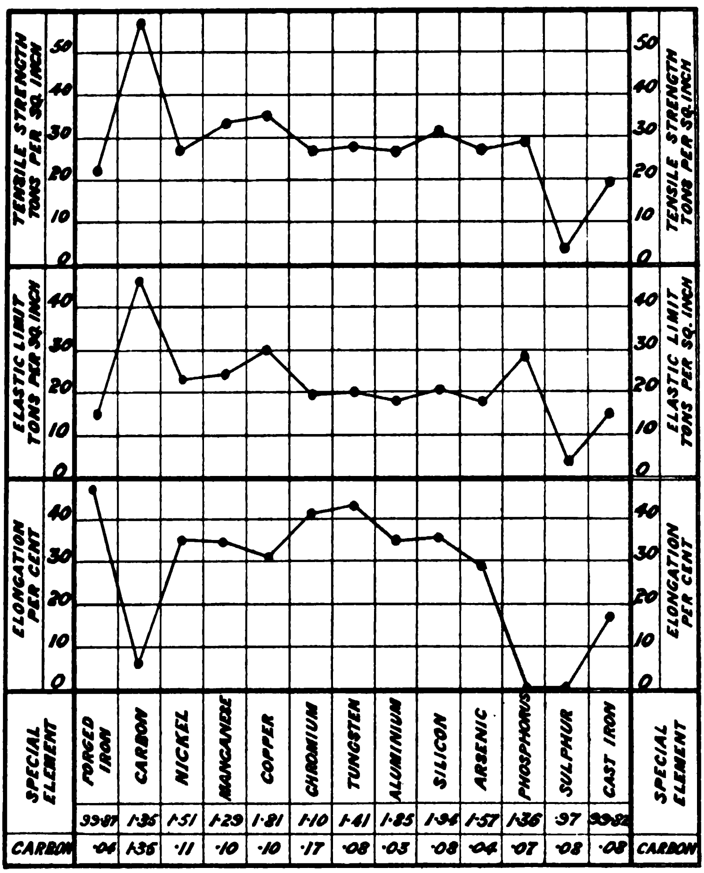


FIG. I.

pure iron. A series of such tests was carried out by Professor Arnold, the results from which were plotted in diagrammatic form by Hatfield, as shown in Fig. I. It should be noted that each of the alloys tested contained a small percentage of carbon.

The tensile strength, elastic limit, and elongation of the various alloys shown on this diagram, clearly indicate the characteristic influence of each element separately in the production of those distinctive properties, the combined effect of which makes either of these qualities of iron to be preferred, according to the particular conditions and structural character of the work to be done.

Iron (pure) is alike the fundamental element in cast iron, wrought iron and mild steel. In cast iron of the ordinary foundry grades, the iron exists as an alloy in the crystalline form of octahedrons, isolated from each other by a flake-like medium of graphitic carbon, clearly defined at the fractured surfaces of the higher grade pigs and other thick portions of iron castings. The size of these crystals and corresponding coarseness of the grain of metal depend on the composition and also to a considerable extent on the rate of cooling. It has been suggested that the apparent superiority of cast iron in resisting corrosion compared to that of mild steel is to some extent due to the presence and protective influence of this matrix or envelope of graphitic carbon which isolates the crystals and thus protects the metal throughout the mass.

Carbon, as has been shown in the diagram, Fig. I., is the element which exerts the greatest influence in changing the physical properties of iron. *In cast iron* it exists, as in pipes, in two distinct conditions, already referred to, as free graphitic carbon and also in the combined state—the relative quantities being influenced by

the amount of silicon, and to a less degree by other elements. A slow rate of cooling facilitates the formation of graphitic carbon, increasing the crystalline structure and corresponding coarseness of the grain exposed by fracture, tending to produce castings which will be softer, tougher, and thus more easily machined or cut with a chisel. On the other hand, rapid cooling, as in the case of chill castings, increases the proportion of combined carbon, and as a result correspondingly harder castings, which are more difficult to machine. *In mild steel* it has been shown in these Tables that the carbon present is wholly in the combined state, and although in comparatively small quantities, compared with that in cast iron, it is nevertheless this element which imparts the outstanding properties to the various qualities of steel, such as, on the one hand, high carbon steel, suitable for edge tools, files, chisels, etc., containing ·790 per cent. carbon, and, on the other hand, low carbon or mild steel, which is stronger and tougher than wrought iron, but equally capable of being forged into shape or welded as, for example, in the manufacture of welded steel tubes.

The influence of carbon on the corrosive properties of iron and steel does not seem to be quite understood, but it is certainly not determined by the total carbon contents, and depends rather on the form in which it exists in combination with the iron. This has been shown by Heyn and Bauer in the *Journal of the Iron and Steel Institute*, 1909, from the results of tests made by them to determine the solubility of steel in sulphuric acid. The results varied for each test piece according to the condition of the carbon content produced by adopting different tempering temperatures, varying from 100° to 640° C.

Silicon in Cast Iron is chiefly of importance owing to

its relative influence in promoting the formation of graphitic carbon in the castings produced, which are thereby made softer, tougher, and less affected by corrosion. The diagram, Fig. I., shows that it increases the strength and elasticity of pure iron at the expense of ductility. The percentage of silicon in castings produced from low grade pig iron is sometimes increased by the addition of ferro-silicon which for foundry purposes contains from 10 to 15 per cent. silicon. Generally speaking, silicon seems to reduce corrosion of iron, and its influence is said to be increased the higher the percentage up to 20 per cent., when the ferro-silicon alloy is practically unaffected by corrosion. It has been suggested, therefore, that the superior property of cast iron to resist corrosive action, compared to that of steel, may be due in a measure to the highly siliconised skin formed by contact of the molten cast metal with the sand (silicon) forming the mould. It is also pointed out by Friend that in India the native made iron, forged on a stone anvil, does not rust like English iron. This has also led to the suggestion that the stone anvil siliconides the skin of the Indian wrought iron and thus accounts for its increased resistance to corrosion.

Sulphur in Cast Iron is chiefly derived from the fuel in the smelting and subsequent remelting processes due to its great affinity for iron. Its presence tends to promote combined carbon. Castings containing a high percentage of sulphur are decidedly hard, shrink more in cooling, and thus set up excessive initial internal stress. Sulphur in mild steel or wrought iron is even more objectionable, as shown in diagram, Fig. I. It is also well known that, in order to avoid the sulphur, the highest qualities of sheet iron are smelted and otherwise heated by means

of wood char fuel, the plates thus produced being known as charcoal iron. The presence of sulphur also produces "red shortness," which interferes with the successful rolling and welding of steel and iron.

In steel the sulphur tends to the formation of sulphides of iron, which subsequently form centres of galvanic action and corrosion, the effect being further influenced by the formation of sulphuric acid due to oxidation of the sulphur. Generally, sulphur when combined with iron or steel increases their liability to corrosive action.

Phosphorus in Cast Iron is derived from the ore and increases the hardness and fluidity of the metal. Up to 1·5 per cent. its presence is considered a distinct advantage in the production of ornamental castings, where strength is of secondary importance. An extreme example of phosphoric iron is known as "cinder pig," which is extremely hard and brittle and is derived from puddler's slag (rich in phosphorus) added when charging the blast furnaces. The influence of phosphorus in steel is to increase corrosion due to segregation, causing irregularities throughout the metal, and resultant local galvanic action when exposed to damp soil. Experiments by Diegel have shown that the corrosive action of sea-water on iron plates is slightly diminished by the addition of phosphorus, the quantity of which varied in each plate from ·01 to ·85 per cent.

In steel, phosphorus produces cold shortness and brittleness, and for the manufacture of pipes the steel plates have been specified in certain cases to contain not more than ·06 per cent. phosphorus.

Manganese, like phosphorus, is derived from the ore, and combines readily with each of the other elements present in cast iron. During the melting process it combines with sulphur to form a fluid compound which

is run off with the melting slag, thus reducing the amount of sulphur and otherwise neutralising the hardening and other effects produced by it.

Manganese in Steel is added along with the recarburiser for the removal of the sulphur, with which it combines to form manganese sulphide, this passing off with the slag, so that only a small amount of manganese remains in the finished steel, as shown in Table II., page 6. Its tendency to increase the corrosion of iron and steel has in some instances been shown when manganese present in the metal varied from ·2 to ·4 per cent.; in other experiments with iron containing from ·4 to 3·0 per cent., the loss in weight by corrosion was even less with the higher percentages of manganese. It is now considered, however, by some authorities that manganese is the chief cause of the excessive corrosive effects on steel, with the result that for the manufacture of mild steel to be used in the production of steel pipes some makers, by the open-hearth process, have endeavoured to eliminate the manganese by raising the working temperature to 1677 degrees Centigrade = (3050 Fah.)—the special quality thus produced being known as "*ingot steel*," the composition of which is stated in Column III. of Table III., page 7, and it has been claimed, as the results of tests with sulphuric acid, that this "ingot steel" is

20 to 40 per cent. less corrosive than wrought iron,
and 40 to 60 ,, ,, ,, soft steel.

Further experience, however, is necessary in order to verify such important claims.

Aluminium, unlike the former elements, is not a natural constituent of iron, and must, therefore, be added either as pure aluminium, which has the low melting point of 1500 degrees Fah., or in the combined form of ferro-

aluminium. Pure aluminium added to the extent of ·056 to ·080 per cent. is said to make cast iron much more fluid, by reason of which the castings produced are sharper, more uniform in texture and free from blow-holes, by breaking up the carbonic acid gas present, forming oxide of aluminium and setting free carbon which combines with the iron: by this means increased strength and other properties are claimed which are not altogether certain. Aluminium does not seem to have any decided influence on the corrosive properties of iron when combined with it to the extent stated, and when combined with iron to the extent of 12 per cent., the metal soon becomes rusted on exposure to damp air.

The importance of chemical composition has all along been recognised by steel makers in order that the various qualities of metal might be produced and maintained with that degree of certainty which is necessary to successfully stand the various physical tests specified and usually carried out under careful inspection.

Iron founders also, who at one time were content to rely on the appearance of fracture, are now better informed, and we find some of the more advanced firms specifying the composition of pig iron required, and at the same time arranging for tests of the material supplied at suitable intervals. Other iron founders have found it a great advantage to employ a chemist as one of the staff, who, along with other important duties, controls the mixing of the various available brands of pig iron in such proportions as to produce castings of predetermined composition, which, along with the usual precautions and practical physical considerations, shall most likely secure the desired result.

STRENGTH AND ELASTICITY OF CAST IRON, WROUGHT IRON, AND MILD STEEL.

The relative characteristic properties of these three metals under tension are graphically shown in the accompanying diagram, Fig. II.

The results shown in this diagram are also stated in the following abstract :

Metal.	Limit of Elasticity (E).	Ultimate Strength.
Cast Iron, - -	7 tons per sq. in.	7 tons per sq. in.
Wrought Iron, -	10 ,, ,,	22·5 ,, ,,
Mild Steel - -	13 ,, ,,	28·0 ,, ,,
Strong Steel, -	25 ,, ,,	52·5 ,, ,,

It is here clearly shown that the behaviour of the three last named metals within the limits of elasticity is somewhat similar as regards the relations between the load and amount of elongation produced. Cast iron, it will be observed on the other hand, has reached the limits of strength and elongation without any decided sign of change, corresponding to the elastic limit, shown at E on the two curves for wrought iron and mild steel. Up to the points E in the diagram the amount of elongation will be found proportional to the stress produced by the load, and up to this point, when the load is removed, the metal regains its normal condition. By continuing to increase the load beyond that at the points E, the proportional

elongation produced ceases, and on the removal of this increased load the metal does not regain its original form, due to permanent extension having taken place. This indicates that the metal becomes broken down and

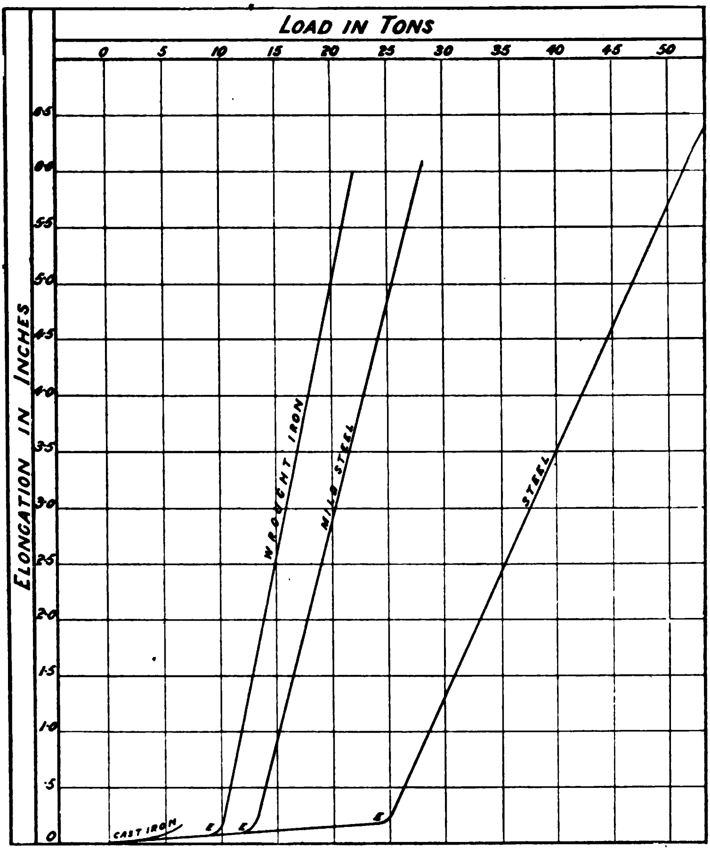


FIG. II.

unreliable when subjected to a load in excess of that at E. As no machine or other structure could be considered safe or otherwise satisfactory which has become distorted and permanently set from any cause, it is important, therefore, in the ordinary course to pro-

vide such structures with a sufficient margin of strength, so that the working stress produced shall not exceed that corresponding to the elastic strength or limit of elasticity.

Table IV. gives the results of tests made to ascertain the ultimate and elastic strengths of the three qualities of metal employed in the construction of pipes, when these are subjected respectively to tension, compression, and shearing stresses.

TABLE IV.

Material.	Breaking Weight.			Elastic Strength.		
	Tension.	Compression.	Shearing.	Tension.	Compression.	Shearing.
	Tons p. sq. in.	Tons p. sq. in.	Tons p. sq. in.	Tons p. sq. in.	Tons p. sq. in.	Tons p. sq. in.
Cast Iron (Unwin),	13·60	58·03				
,, ,,	7·81	42·41	12·72	4·68	9·37	3·52
,, (D. K. Clark),	6·00	30·00	—	—	—	—
,, ,,	10·00	46·00	—	—	—	—
Wrought Iron Plates,	18·00	16·00	16·00	11·00	—	—
$\frac{3}{8}''$ to $\frac{5}{8}''$ thick, - -	21·00	20·00	20·00	12·00	—	15·00
W.I. Bars (Unwin),	30·00	—	—	—	—	—
,, ,,	25·44	23·22	23·22	10·71	10·71	9·00
,, ,,	15·00	—	—	—	—	
,, (D. K. Clark),	18·80	65·45	15·20	11·05	10·74	
Mild Steel, - -	28·00	—	21·00			
,, - -	32·00	—	25·00			
Special Mild Steel, -	24·00					
,, ,, ,, -	36·00					

Table V. may be taken as representing more particularly the tensile strength and elasticity of rolled iron and mild steel sheets such as are used for the manufacture of rivetted and welded steel pipes generally. The reduction in strength at the welded joint, compared with that of the full section of the plate, is also added.

TABLE V.

	Along the Grain. Ultimate Tensile Strength.			Across the Grain. Ultimate Tensile Strength.		
	Tons p. sq. in.	Pounds p. sq. in.	Elongation in a length of 8 inches.	Tons p. sq. in.	Pounds p. sq. in.	Elongation %.
			Per cent.			
Rolled Iron Sheets,	20	44,800	15	16	35,840	5
Mild Steel Sheets,	24	53,760	20 to 30	Practically the same results across the grain.		
” ” ”	26	58,240	20 to 28			
” ” ” (Siemens-Martin) *Open Hearth*	28	62,720	20 to 26			
Lap Welded Joints (Steel) Plates $\frac{1}{8}''$ to $\frac{1}{4}''$ thick steel 68 per cent. efficiency, -	17·7	39,600				
Do. do. $\frac{5}{16}''$ to $\frac{1}{2}''$ thick 80 per cent. efficiency,	20·8	46,592				

Note :—The elongation generally increases as the tensile strength diminishes. Specifications usually provide for a tensile strength from 26 to 28 tons per sq. inch, and an elongation in a length of 8 inches not less than 20 per cent.

Engineers, in order to secure the best standard practice as regards the quality of metal used in the manufacture of cast iron pipes, require that a Transverse Test Bar be made from the metal used in each day's cast. The test bar usually specified is 2 inches deep, 1 inch thick, and 42 inches long, and when supported on knife edges 36 inches apart, it shall be capable of carrying a load not less than 28 hundredweights or more than 32 hundredweights, when gradually applied and concentrated at the centre. The deflection before fracture takes place must be not less than ·380 of an inch. It is also usually specified that the quality of metal shall be uniform and close grained throughout, and such that it can be readily cut or chipped with a chisel and easily bored for branch connections.

Figure III. shows two different arrangements of test bar referred to, under a transverse load, the one shown at (*a*) being that usually employed.

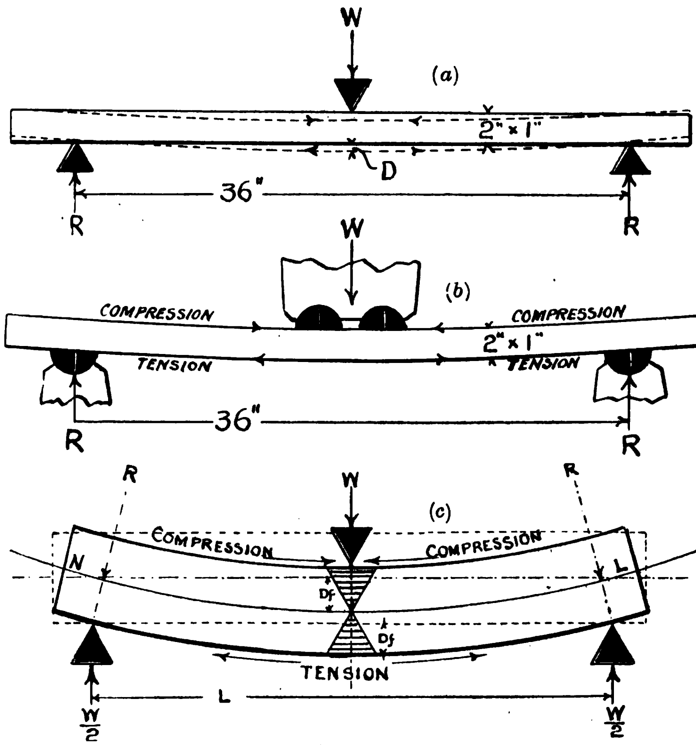


FIG. III.

In taking the bent form shown dotted at (*a*) when under a transverse load, the metal, in the lower section, becomes extended or lengthened, while that of the upper section is compressed or shortened, the stress at any point being in proportion to its distance from the neutral axis N.L., as indicated by the horizontal lines within the two triangles shown at (*c*), which represent the maximum stresses at the highest and lowest points of the section and also

show how they gradually diminish to zero at the neutral axis N.L.

The relation that exists between the load, size of section, distance between the points of support, and the strength of material is stated in the following simple formulae, derived from fundamental considerations regarding the bending moments and moments of resistance of the material:

W	= The breaking weight in tons, cwts., or lbs. per sq. in.			
S	= The ultimate tensile strength	,,	,,	,,
Se	= The elastic strength	,,	,,	,,
L	= The span or distance between supports in inches.			
B	= The breadth of beam or bar		,,	,,
D	= The depth ,, ,,		,,	,,
R	= The radius of curvature at bottom		,,	,,
E	= The coefficient of elasticity		,,	,,
1/E	= The fraction of the length by which a beam is extended below or shortened by compression above for *each ton* of direct stress per square inch within the elastic limit (at the extreme top and bottom fibres).			
Df	= The deflection in inches.			

$$\left(\begin{array}{c}\text{Bending Moment}\\\text{due to Load.}\end{array}\right) = \left(\begin{array}{c}\text{Moment of Resistance of Beam.}\\\text{Rectangular Section.}\end{array}\right)$$

$$\frac{WL}{4} = \cdot 2888BD^2S;$$

$$\therefore \quad W = 4 \times \frac{\cdot 2888BD^2S}{L} = \frac{1 \cdot 1552BD^2S}{L},$$

$$\therefore \quad S = \frac{WL}{1 \cdot 1552 \times BD^2}.$$

To ascertain the theoretical tensile strength of cast iron in a test bar of standard dimensions that breaks under a

concentrated load of 30 cwts. placed at the centre, we simply substitute the values as follows :

			Per sq. in.
Test bar breaking at 30 cwts.	$S = \dfrac{30 \times 36}{1·1552 \times 1 \times 2^2}$	=	233·72 cwts.
	$= 30 \times ·3895$	=	11·68 tons.
Do. at 32 ,,	$S = 32 \times ·3895$	=	12·46 ,,
Do. at 28 ,,	$S = 28 \times ·3895$	=	10·90 ,,
Do. at 26 ,,	$S = 26 \times ·3895$	=	10·13 ,,
Do. at 24 ,,	$S = 24 \times ·3895$	=	9·35 ,,

The actual strength of a casting may be greater or less than that of the test bar of the same metal, depending on the rate of cooling, due to thickness of metal and other incidental causes. In a cast iron pipe, however, which is circular in form and practically uniform in thickness throughout, the results from a test bar may be accepted as a true index of the strength and elasticity of the metal in the pipe from the same cast.

Deflection of a beam or test bar, as shown in Fig. III., has already been referred to as the result of stretching under tension and shortening under compression, and as a means of ascertaining the elastic properties of the material it is important that these two conditions of stress should be examined and considered in detail.

The amount of deflection in terms of the length of the test bar and radius of the bar's curvature, as derived from the properties of a circle, is :

$$Df = \frac{L^2}{8 \times R}.$$

In terms of ultimate strength of the material

$$Df = \frac{S \text{ tons per sq. in.} \times L^2}{4 \times DE}.$$

∴ The ultimate tensile strength of the material may be expressed as follows :

$$S \text{ tons per sq. inch} = \frac{Df \times 4 \times DE}{L^2}.$$

Equating the two values of S in tons per square inch, as found on pages 20 and 21, we obtain the following :

$$\frac{WL}{1{\cdot}1552 \times BD^2} = \frac{Df \times 4 \times DE}{L^2};$$

$$\therefore \text{ Deflection } Df = \frac{WL \times L^2}{1{\cdot}1552 \times 4 \times BD^3E} = \frac{WL^3}{4{\cdot}62BD^3E}.$$

The value of E in this equation, representing the coefficient or modulus of elasticity for cast iron, may be obtained as in the undernoted calculations from results of tests made with cast iron bars one square inch in section and ten feet long, from which the maximum tensile strength obtained was 6½ tons per square inch. The amount of extension and compression observed for each additional load of one ton is shown in Fig. IV., and the results of tensile tests are also detailed in the following abstract of same data :

Cast Iron Test Bar. One square inch section. 10 feet long in tension.				Extension in 10 feet in inches.		Difference per ton in inches.
1	ton per sq. inch	produced	=	·0196	=	·0196
2	do.	do.	=	·0418	=	·0222
3	do.	do.	=	·0656	=	·0238
4	do.	do.	=	·0932	=	·0276
5	do.	do.	=	·1232	=	·0300
6	do.	do.	=	·1610	=	·0378
						·1610

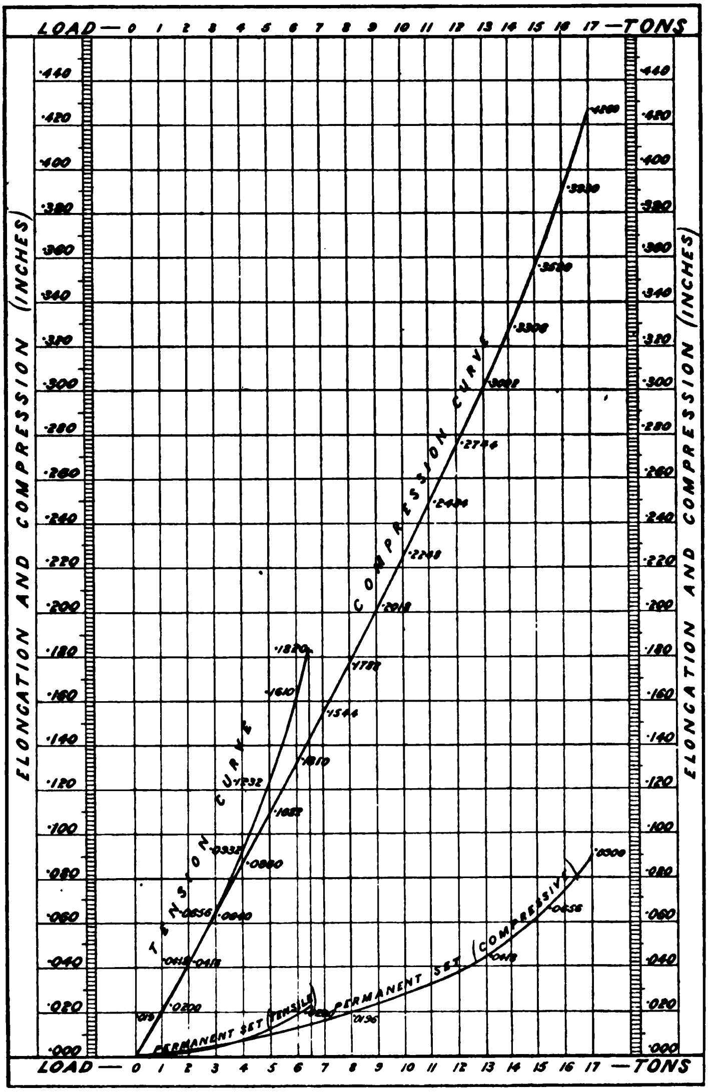

LOAD — 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 — TONS
ELONGATION AND COMPRESSION (INCHES)
·440 ·420 ·400 ·380 ·360 ·340 ·320 ·300 ·280 ·260 ·240 ·220 ·200 ·180 ·160 ·140 ·120 ·100 ·080 ·060 ·040 ·020 ·000
TENSION CURVE
COMPRESSION CURVE
PERMANENT SET (TENSILE)
PERMANENT SET (COMPRESSIVE)
·1820
·1610
·1544
·2774
·0220
LOAD — 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 — TONS

FIG. IV.

$\therefore$ Average extension per ton $= \dfrac{\cdot 1610}{6} = \underline{\cdot 0268}$ inch.

$$\frac{\text{Rates of extension per ton}}{\text{Total length of test bar}} = \frac{\cdot 0268}{120 \text{ ins.}} = \frac{1}{4477} = \frac{1}{E}.$$

$\therefore$ The coefficient or modulus of elasticity $= \underline{4477}$ tons per square inch.

i.e. The load which would stretch a cast iron bar to double its length if supposed to go on stretching at the same average rate per ton without breaking, $= 4477 \times 2240$. $= 10{,}028{,}480$ pounds per square inch. = Modulus of elasticity (E).

Substituting the dimensions of the cast iron test bar for which

The value of E - - - -	= 4477 tons
and transverse breaking load -	= 30 cwts.
	= 1·5 tons.

$\therefore$ The derived theoretical deflection is—

$$Df = \frac{WL^3}{4{\cdot}62 \times BD^3E} = \frac{1{\cdot}5 \times 36^3}{4{\cdot}62 \times 1 \times 2^3 \times 4477} = \cdot 42 \text{ inch.}$$

The minimum deflection (Df) allowed as per specification referred to on page 18	= ·38 ,,
Taking the modulus of elasticity (E) as 5000 tons, the theoretical deflection works out - - - - - - -	= ·375 ,,

For different qualities of cast iron the value of E may vary from 6230 tons to 5966 tons. See D. K. Clark's *Rules and Tables*.

The amount of deflection obtained by calculation is thus quite consistent with the terms of specification referred to on page 18.

TRANSVERSE STRENGTH OF MILD STEEL.

Take a bar of mild steel of dimension $2'' \times 1'' \times 42''$ supported on knife. edges 36 inches apart, and loaded at the centre as shown in Figure III.; the deflection of the mild steel test bar, as compared with that of the cast iron test bar of the same dimensions, will be directly proportional to the amount of stretching produced in each under the same loads, within the limits of elasticity.

In diagram Figure IV. and the accompanying abstract (page 22), is shown the extension of a cast iron test bar 1 square inch in section and 10 feet long, for each additional load of one ton up to the breaking load of $6\frac{1}{2}$ tons per sq. inch; also the average extension per ton per sq. inch $= {\cdot}0268$ inch. If we compare this with the relative curves for cast iron and mild steel shown in Figure II., the extension of mild steel is represented as approximately one-third that of cast iron. The corresponding average extension of a mild steel bar 10 feet long within the limits of elasticity will therefore be approximately

$$\frac{\cdot 0268}{3} = \cdot 0089 \text{ inch for each ton per sq. inch.}$$

$$\therefore \text{ E for cast iron} = \frac{120}{\cdot 0268} \text{ inches} = 4477 \text{ tons per sq. in.,}$$

$$\text{and E for mild steel} = \frac{120}{\cdot 0089} \text{ inches} = 13{,}490 \text{ tons per sq.in.}$$

D

tons per sq. inch

Given S = Ultimate tensile strength of mild steel = 28
and S^e = Elastic strength " " = 13,

we obtain the following relations as stated on page 20 :

W = Ultimate transverse breaking load for a mild steel bar in Tons,

$$\therefore W = \frac{4 \times \cdot 2888 \times BD^2 \times 28}{L}$$

For a Test Bar 1″ × 2″ × 36 inches between the points of support

$$W = \frac{4 \times \cdot 2888 \times 1 \times 2^2 \times 28}{36} = 3 \cdot 5939 \text{ tons}$$

$$= 71 \cdot 878 \text{ cwts.}$$

Similarly W^e = Elastic transverse load

$$= \frac{4 \times \cdot 2888 \times 1 \times 2^2 \times 13}{36} = 1 \cdot 6686 \text{ tons}$$

$$= 33 \cdot 372 \text{ cwts.}$$

∴ Deflection of mild steel under a transverse load within the elastic limit as stated in pages 21 and 22 is :

$$Df = \frac{W^e \times L^3}{4 \cdot 62BD^3E} = \frac{1 \cdot 6686 \times 36^3}{4 \cdot 62 \times 1 \times 2^3 \times 13600} = \cdot 1548 \text{ inch.}$$

The following results were obtained from transverse tests made on wrought iron bars of various sizes and span. See D. K. Clark's *Tables.*

TABLE VI.

Metal.	Test Bar. Breadth.	Depth.	Span.	Elastic Strength. Tensile.	Transverse Load. Calculated.	Observed.	Deflection at Elastic Limit. Load.	Deflection.
	ns.	ins.	ins.	tons per sq. in.	tons.	tons.	tons.	ins.
W.I.	2 ×	2	× 33	9·5	2·66	2·50	2·50	·100
,,	1·5 ×	3	× 33	10·0	4·72	4·25	4·00	·088
,,	1·5 ×	3	× 33	10·0	4·72	4·25	4·00	·102
,,	1·5 ×	2·5	× 33	10·0	3·28	3·00	4·00	·104
*M.S.	1·0 ×	2·0	× 36	13·0	1·66	—	1·66	·1548

* From the foregoing calculated results.

TABLE VII.

Metal. Swedish Iron.	Test Bar. Breadth.	Depth.	Span.	Ultimate Strength. Tensile direct.	Transverse Load. Calculated.	Observed.	Deflection at Elastic Limit. Load.	Deflection.
	ins.	ins.	ins.	tons per sq. in.	tons.	tons.	tons.	in.
W.I.	2·04	× 2·02	× 25	18·8	7·230	7·093	3·348	·089
,,	2·02	× 2·02	× 25	,,	7·302	6·646	3·125	·088
,,	1·95	× 2·02	× 25	,,	6·911	6·234	2·679	·072
,,	2·00	× 2·00	× 25	,,	6·948	5·955	2·679	·072
M.S.*	1·00	× 2·00	× 36	28·0	3·593	—	1·668	·154

* From the foregoing calculated results.

Taking the relative strength or stiffness of two 24″ pipes of cast iron and mild steel respectively, under an external load, as indicated roughly by the transverse strength of the following two test bars, which represent the thicknesses of metal in these two pipes, viz. :

Cast iron, 1 inch broad $\frac{15}{16}$″ thick = ·938 inch
Mild steel, 1 ,, ,, $\frac{5}{16}$″ ,, = ·312 ,,

the elastic transverse strengths of these two bars when resting on the flats between supports 36 inches apart, are derived from the foregoing formula (page 20), as follows:

$$\text{W tons} = \frac{4 \times \cdot 2888 BD^2 \times S}{L}$$

in which $\frac{4 \times \cdot 2888B}{L} = \frac{4 \times \cdot 2888 \times 1}{36} = \cdot 0321$ is constant.

The relative strengths of these two test bars may now be represented by the modified formula in which values of W tons $= \cdot 0321 \times D^2 \times S$.

The tensile and corresponding transverse loads are therefore as follows, viz.:

	Tensile Stress. *Ultimate.* tons p. sq. in.	*Elastic.* tons p. sq. in.
S_c = Tensile strength of cast iron	= 11	4·68
S_s = ,, ,, mild steel	= 28·0	13·00

$\therefore$ W for cast iron (ultimate) $= \cdot 0321 \times \cdot 938^2 \times 11 \cdot 00$
$= \cdot 310$ tons $= 6 \cdot 200$ cwts.

W^e ,, ,, (elastic) $= \cdot 0321 \times 938^2 \times 4 \cdot 68$
$= \cdot 132$ tons $= 2 \cdot 643$ cwts.

W for mild steel (ultimate) $= \cdot 0321 \times \cdot 312^2 \times 28 \cdot 00$
$= \cdot 087$ tons $= 1 \cdot 749$ cwts.

W^e ,, ,, (elastic) $= \cdot 0321 \times \cdot 312^2 \times 13 \cdot 00$
$= \cdot 040$ tons $= \cdot 800$ cwts.

The relative strengths of cast iron and steel pipes on the foregoing bases are therefore:

Ultimate Strength.

$$\frac{W^c \text{ for cast iron pipe } \overset{\text{thick}}{\cdot 938''}}{W^s \text{ for mild steel pipe } \cdot 312''} = \frac{6 \cdot 200}{1 \cdot 749} = \frac{3 \cdot 55}{1}.$$

Elastic Strength.

$$\frac{W^c \text{ for cast iron pipe } \overset{\text{thick}}{\cdot 938''}}{W^s \text{ for mild steel pipe } \cdot 312''} = \frac{2 \cdot 643}{\cdot 812} = \frac{3 \cdot 25}{1}.$$

It will thus be seen that so far as the results for transverse strength may be taken as indicating the resistance under external loads, the 24 inch cast iron pipe is much stronger than the relatively thin mild steel pipe usually supplied for the same internal working pressure.

The collapsing strength of pipes under external loads will be referred to more fully later on (page 50).

RESISTANCE OF PIPES AND HOLLOW CYLINDERS TO BURSTING.

The direct effect of internal fluid pressure within a pipe or hollow cylinder is to stretch the material of the shell circumferentially and correspondingly increase the diameter. When the thickness of the shell is small compared with the diameter, as, for example, the larger sizes of ordinary water-pipes, the stress produced is practically uniform throughout its thickness, and the relation between bursting effort and resistance of material is represented as follows :

Bursting effort = Resistance of material.

(1) $P \times d = 2 \times t \times S \times 2240.$

On the other hand, when the thickness of metal is considerable in relation to the diameter, as in the case of small sizes of pipe, high pressure hydraulic cylinders, etc., the stress produced throughout the thickness of metal is not uniform. The maximum stress and corresponding strain or stretching effect is at the inner surface of the metal and diminishes towards the outer skin of the pipe inversely as the radial dimensions.

The equation then becomes :

(2) $P \times d = d \times$ hyperbolic log of $R \times S \times 2240$;

$$\therefore\ P = \text{hyperbolic log of } \frac{r'}{r} \times S \times 2240.$$

The importance of recognizing the latter formula (2) for the thickness of metal in hydraulic pipe or cylinders will be seen from the following example, viz.:

By formula (1)

Resistance of metal = $(2 \times t \times S \times 2240)$ lbs.

By formula (2)

Resistance of metal = $(d \times \text{hyp. log} \frac{r'}{r} \times S \times 2240)$;

The ratio of strengths obtained by formulae (1) and (2) for a pipe 12″ dia. and 2″ thick is as follows:

$R = \frac{r'}{r} = \frac{8}{6} = 1{\cdot}333$ and the hyp. log of $1{\cdot}333 = {\cdot}2852$.

$$\therefore \frac{\text{Formula (1)}}{\text{Formula (2)}} = \frac{2 \times t}{d \times \text{hyp. log} \frac{r'}{r}} = \frac{2 \times 2}{12 \times {\cdot}2852}$$

$$= \frac{4}{3{\cdot}4224} = \frac{100}{85{\cdot}56}.$$

From this it will be seen that by formula (1) the resultant thickness of metal is 14·44 per cent. less compared to that by the more correct formula (2) in the foregoing example.

The letters used in these calculations are:

P = Bursting pressure in *pounds* per square *inch*,
D = Outside diameter of pipe or cylinder in *inches*,
d = Inside „ „ „ „ „
r^l = Outside radius „ „ „ „
r = Inside „ „ „ „ „
t = Thickness of metal „ „ „ $= \frac{D-d}{2}$,
S = Ultimate tensile strength of metal in *tons* per sq. in.
R = Ratio of outside to inside diameter $= \frac{D}{d} = \frac{r'}{r}$.

If again we take a series of cast iron hydraulic cylinders 10 inch diameter inside, but of varying thicknesses from 5 inch thick down to $\frac{3}{8}$ (·375) inch thick, the bursting pressures are as follows :

TABLE VIII.

Cylinder.		Ratio R. $\frac{D}{d}$	Hyp. log R.	Bursting Pressure. (Hyp. log R × S).	Proportional Thicknesses of Metal.	Proportional Bursting Pressures.
Bore inches.	Thick inch.					
diam.				tons per sq. in.		
10″	5·000	2·000	·693	5·544	1·0000	1.000
10″	2·500	1·500	·405	3·240	·5000	·584
10″	1·250	1·250	·223	1·784	·2500	.321
10″	·750	1·150	·139	1·112	·1500	.200
10″	·375	1·075	·072	·576	·0750	·104

Ultimate tensile strength of cast iron = 8 tons per sq. inch.

In the case of wrought iron and steel cylinders of considerable thickness, owing to the elastic properties of these metals, the stresses produced throughout the thickness do not vary in the same proportions as that for cast iron, and the formula representing the relations between bursting effort and resistance of thick mild steel cylinders becomes :

$$Pd = 2 \times \frac{S}{2}\{(r' - r) + r \text{ hyp. log R}\} ;$$

$$\therefore P = \frac{2 \times \frac{S}{2}\{(r' - r) + r \text{ hyp. log R}\}}{2r}$$

$$= \frac{S\{(R - 1) + \text{hyp. log R})\}}{2}.$$

The ultimate strength of thick mild steel cylinders of the same dimensions as the foregoing are shown in Table IX.

TABLE IX.

Ratio. $R=\frac{D}{d}$.	Hyd. Cylinders. Bore inches.	Hyd. Cylinders. Thickness.	Hyd. log R.	Value of $\frac{(R-1)+\text{Hy. log } R}{2}$	Bursting Pressure. $\frac{(R-1)+\text{Hy. log } R}{2}\times S$.	Proportional Thickness of Metal.	Proportional Bursting Pressure.
	diam.	ins.			tons per sq. in.		
2·000	10″	5·000	·693	·8465	23·702	1·0000	1·000
1·500	10″	2·500	·405	·4525	12·670	·5000	·534
1·250	10″	1·250	·223	·2365	6·622	·2500	·279
1·150	10″	·750	·139	·1445	4·046	·1500	·170
1·075	10″	·375	·072	·0735	2·058	·0750	·086

Ultimate tensile strength of steel = 28 tons per sq. inch.

The relative strengths of hydraulic cylinders of cast iron and mild steel as shown in Tables VIII. and IX. may be stated generally as follows :

Bursting pressures for

Cast Iron Cylinders - $= S^c \times \text{hyp. log } R.$

Mild Steel ,, - $= \dfrac{S^s\{(R-1)+\text{hyp. log } R\}}{2}.$

THICKNESS OF PIPES AND HOLLOW CYLINDERS.

When a pipe is required for normal conditions of internal fluid pressure, as, for example, underground pipes for water, gas, air, sewage, etc., the thickness of metal required is generally of small dimensions compared to the diameter; it is, therefore, the usual practice to ascertain the thickness of metal by approximate rules instead of by the more elaborate formulae referred to in the case of high internal pressures and hydraulic work generally.

The simplest form of equation representing the bursting effort and the corresponding stress produced in the metal of the pipe is that stated in page 30, viz.:

$$P \times d = 2 \times t \times S \times 2240 ; \ldots\ldots (1)$$

$$\therefore \text{ Theoretical thickness } t'' = \frac{Pd}{2 \times S \times 2240} = \frac{Pd}{4480 \, . \, S}.$$

In practice, however, the thickness of metal thus obtained for ordinary working pressures would obviously be insufficient to stand the rough usage in handling, apart from the practical difficulties to be overcome in the various processes of manufacture peculiar to the different materials used, and indeed the internal fluid pressure in some instances becomes a comparatively small factor in deciding the thickness of metal compared to that required to meet the various practical considerations, more particularly in the case of light pressures.

For pipes required to convey water under pressures corresponding to normal working conditions, the thickness for successful practice depends also on the discretion of the engineer, who requires to take into consideration special conditions. Various rules and formulae have been suggested from experience and practised by different authorities to express the proper thickness of metal in terms of the controlling factors.

The following simple formula (2) represents Bateman's practice :

$$\text{Thickness } t'' = \frac{\mathrm{P}d}{4250} + \cdot 25''. \quad \ldots\ldots\ldots\ldots (2)$$

By comparing the formula (2) with the foregoing theoretical formula (1), we can ascertain the additional thickness which Mr. Bateman decided upon as good practice for cast iron pipe. This additional thickness, therefore, represents also the margin of strength or factor of safety adopted by him for ordinary working pressures.

The factor of safety (F) according to Bateman's practice may be obtained thus, viz. :

$$\mathrm{F} = \frac{\text{Bateman's formula}}{\text{Theoretical formula}} = \frac{\dfrac{\mathrm{P}d}{4250} + \cdot 25}{\dfrac{\mathrm{P}d}{4480 \,.\, \mathrm{S}}} \ldots\ldots (3)$$

Using this formula (3) the factors F in Bateman's practice for the following conditions of pressure, etc., work out, as stated in column C, Table X. :

Internal working pressure P = 133 lbs. per sq. inch.
Hydraulic test pressure = 2P = 266 „ „
„ „ „ = 600 feet head.
Ultimate tensile strength of cast iron taken } = 8 tons per sq. inch.

TABLE X.

Bore. Diameter in ins.	Bateman's Practice.			Ordinary Practice.		
	A. Thickness by Formula 1.	B. Thickness by Formula 2.	C. Factor F. Formula 3.	D. Thickness in Sixteenths.	E. Thickness in Decimals.	F. Factor F. Formula 3.
	ins.	ins.		ins.	ins.	
3	·01113	·3436	30·8	$\frac{3}{8}$ bare	·3436	30·8
6	·02226	·4372	19·6	$\frac{7}{16}$	·4375	19·6
9	·03339	·5308	15·9	$\frac{9}{16}$	·5625	16·8
12	·04452	·6244	14.0	$\frac{5}{8}$	·6250	14·0
15	·05565	·7180	12·9	$\frac{11}{16}$	·6875	12·3
18	·06678	·8116	12·1	$\frac{13}{16}$	·8125	12·1
24	·08904	·9988	11·2	1	1·0000	11·2
30	·11130	1·1860	10·6	$1\frac{3}{16}$	1·1875	10·6
36	·13356	1·3730	10·3	$1\frac{3}{8}$	1·3750	10·3
42	·15582	1·5604	10·0	$1\frac{9}{16}$	1·5625	10·0
48	·17808	1·7476	9·8	$1\frac{3}{4}$	1·7500	9·8

Columns D, E, and F give the thickness of metal and corresponding factors F for cast iron pipe for working pressures from 133 to 150 pounds per square inch, in accordance with the usual practice.

Columns B and C give the thickness of metal and corresponding factors F derived from Bateman's Formula (2) for the same working pressure.

Comparing the thicknesses and factors F obtained by Bateman's formula (2) in columns B and C with those representing common practice in columns D, E, and F, Table X., it will be seen that they agree approximately throughout. If, however, the same formula (2) is used to ascertain the thickness of metal for working pressures higher or lower than the normal conditions of pressure the results will be found to differ more or less from the usual practice of engineers, as the working pressure increases or diminishes. Generally speaking, such formulae are only satisfactory within narrow limits

of pressure owing to the use of a constant instead of a variable factor, such as F in column F, Table X. In these examples it should be noted that the different factors F stated are for differences in diameter of pipe only, as the working pressure is the same throughout. In order, then, to obtain the proper thicknesses of metal for the same range of diameters, but for different working pressures, the factor F must also change so that the thicknesses obtained by such factors shall not only vary rationally but shall at the same time be within the range of thicknesses usually specified by leading engineers in their ordinary practice.

Assuming that a proper series of variable factors F has been ascertained, then the proper thicknesses may be derived from the theoretical formula (1) by simply introducing the additional factor F as follows :

$$\mathrm{P}d = 2t'' \times \frac{\mathrm{S}}{\mathrm{F}} \times 2240;$$

$$\therefore t'' = \frac{\mathrm{P}d\mathrm{F}}{2 \times \mathrm{S} \times 2240} = \frac{\mathrm{P}d\mathrm{F}}{4480 \,.\, \mathrm{S}}. \quad \ldots\ldots.(4)$$

To obtain rational factors F for all diameters and conditions of working pressures, the author has carefully analysed the latest practice of engineers and cast iron pipe founders. The results of these investigations are graphically shown in Fig. VII., from which the thickness of metal for any diameter of pipe and working pressure is readily obtained by simply measuring the height of the vertical ordinate from the point on the bottom line indicating the diameter on the horizontal scale up to the point where the vertical line intersects the inclined line of thicknesses corresponding to the particular working pressure specified.

In constructing a diagram of this kind, it is necessary, in the first place, to ascertain the factors F and correspond-

ing thicknesses of metal for the different working pressures of two diameters, preferably the factors F for the diameters at each end of the scale, and it is the method employed here to fix these factors F that constitutes the leading features of this system for obtaining thicknesses which shall vary in rational proportions throughout for all diameters and working pressures within the scope of the diagram. The factors F referred to and shown on the scale at the extreme ends of the diagram Fig. VI., are derived from the regular curves shown on diagram Fig. V., the latter of which represent the average result obtained from analyses of the thicknesses for the different pressures shown as specified by different authorities. It should be mentioned, however, that the factors F obtained from analysis of these examples in practice varied considerably, but they were generally found to follow approximately the same law as that indicated by the curves shown.

Having thus decided on a rational method for obtaining the thicknesses shown graphically in Fig. VII., it will be found that the thicknesses for all diameters and working pressures given in this diagram and Tables XIV. and XV., give factors F which vary in accordance with different regular curves as shown for each working pressure on diagram Fig. VI. These curves are also in accordance with the results derived from calculations for each thickness and working pressure.

In considering these various factors F for cast iron pipe, it should be noticed that, although it becomes less as the working pressure is increased, the margin of strength is actually increased as shown in the foregoing Table XI. for a pipe 36 inches diameter.

Table XII. gives the various thicknesses of metal in decimals derived from the diagram Fig. VII.

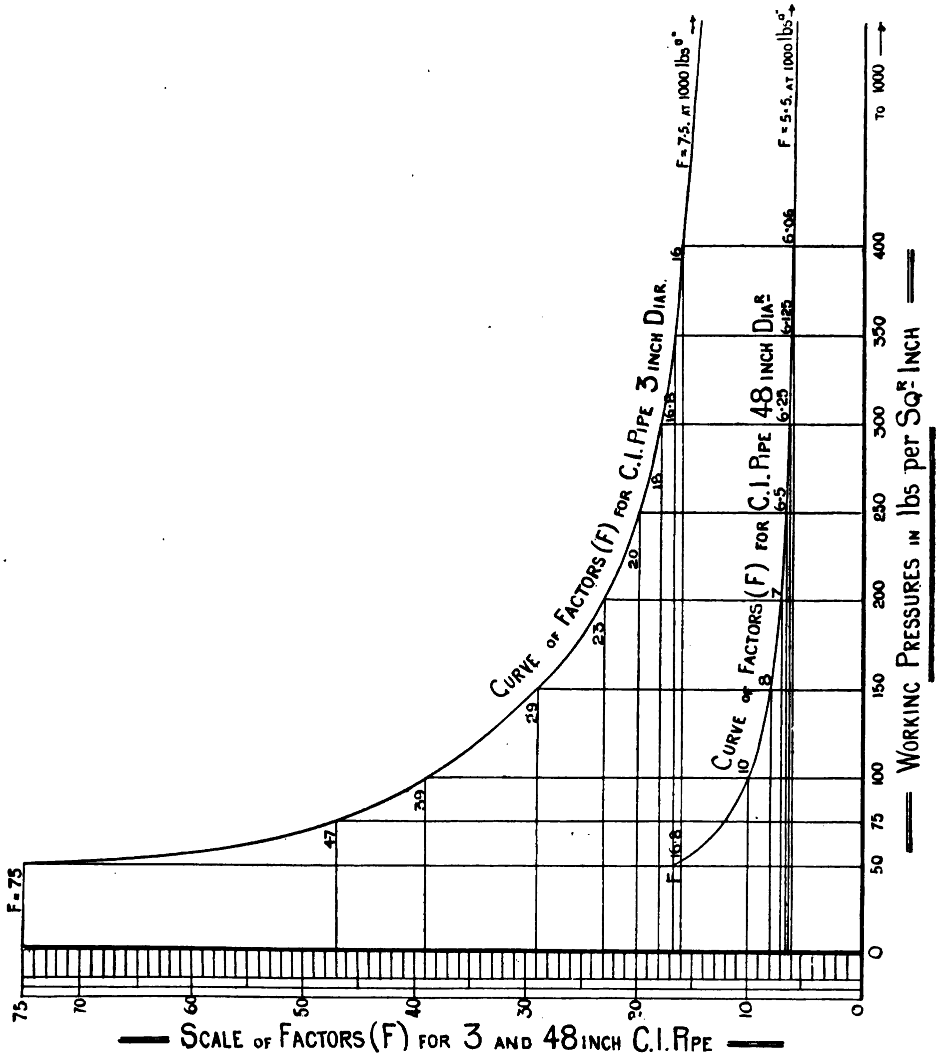


FIG. V.

Facing p. 38.

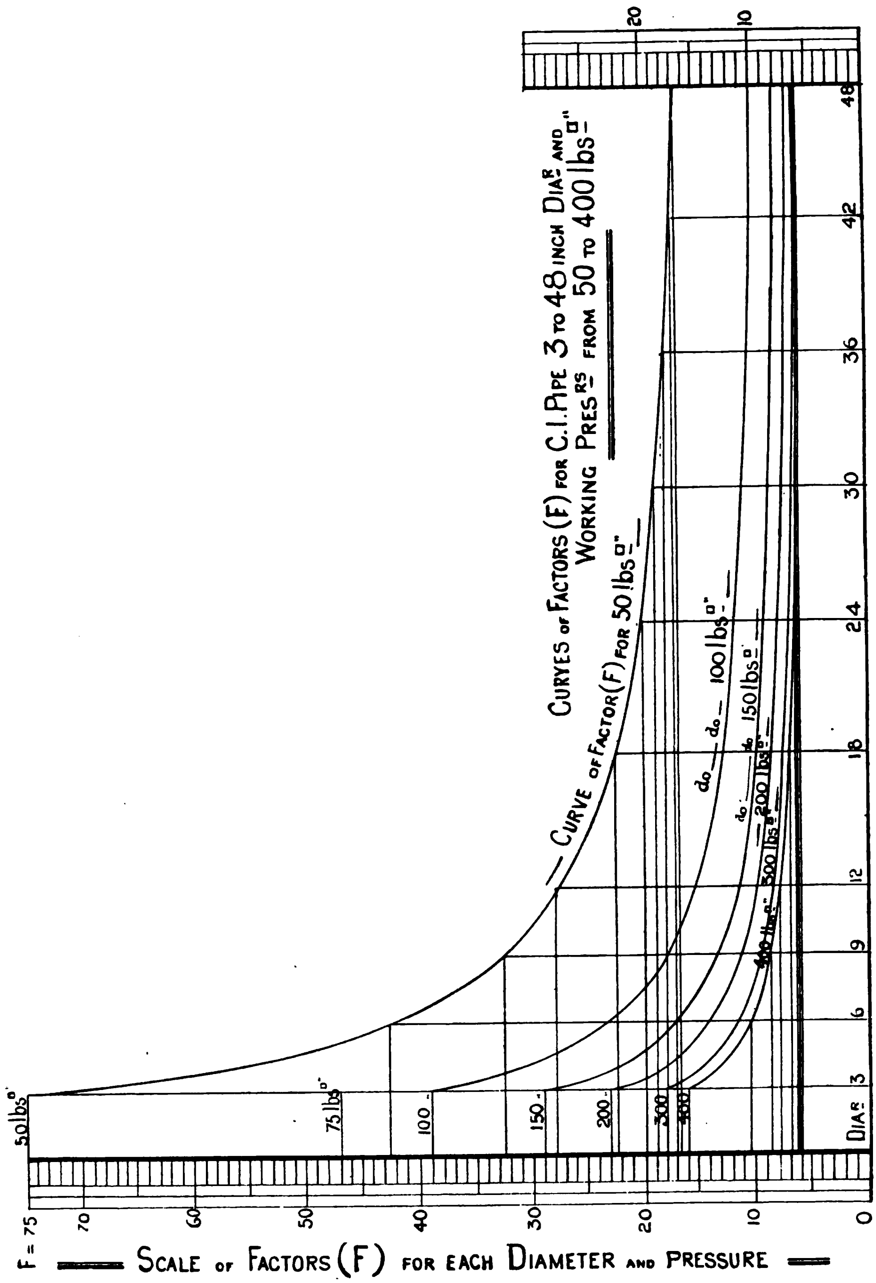
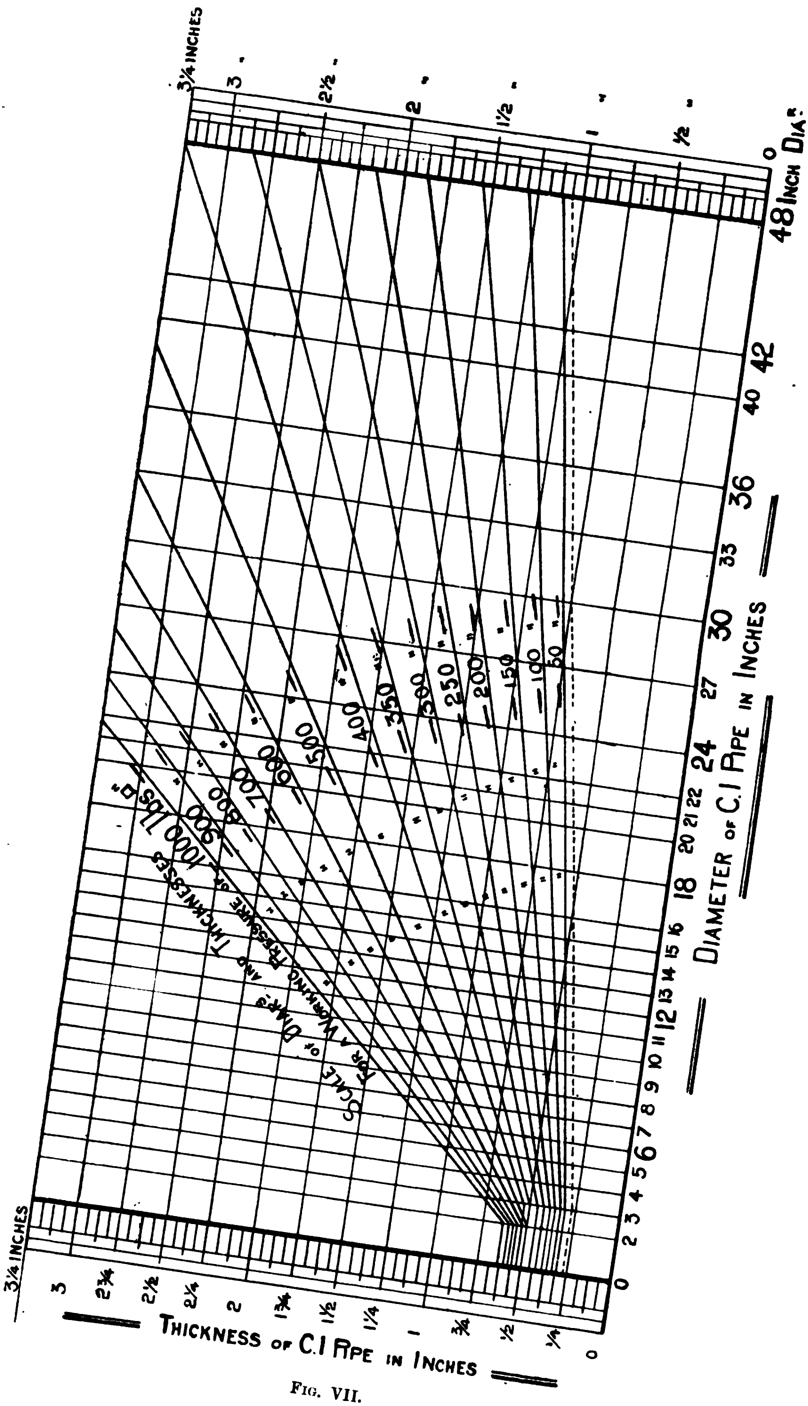

Curves of Factors (F) for C.I. Pipe 3 to 48 inch Diar. and Working Presrs. from 50 to 400 lbs. □"
Curve of Factor (F) for 50 lbs. □"
do do 100 lbs. □"
do 150 lbs. □"
do 200 lbs. □"
300 lbs. □"
400 lbs. □"
50 lbs. □"
75 lbs. □"
100
150
200
300
400
Diar.
3
6
9
12
18
24
30
36
42
48
20
10
F = 75
70
60
50
40
30
20
10
0
Scale of Factors (F) for each Diameter and Pressure

Fig. VI.



3¼ INCHES
3
2½
2
1½
1
½
0
48 INCH DIAR.
42
40
36
33
30
27
24
22
21
20
18
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
0
DIAMETER OF C.I PIPE IN INCHES
SCALE OF DIAM'S AND THICKNESSES FOR A WORKING PRESSURE OF
1000 lbs
900
800
700
600
500
400
350
300
250
200
150
100
50
3¼ INCHES
3
2¾
2½
2¼
2
1¾
1½
1¼
1
¾
½
¼
0
THICKNESS OF C.I PIPE IN INCHES

FIG. VII.

TABLE XI.

Working Pressure. Pounds per sq. in.	Factors F for 36″ diam.	Margin of Strength. (F - 1) × Working Pressure.
50	18·0	17·5 × 50 = 850 lbs.
100	10·5	9·5 × 100 = 950 „
150	8·5	7·5 × 150 = 1125 „
200	7·5	6·5 × 200 = 1300 „
250	7·0	6·0 × 250 = 1500 „
300	6·5	5·5 × 300 = 1650 „
350	6·38	5·38 × 350 = 1883 „
400	6·25	5·25 × 400 = 2100 „

TABLE XII.

THICKNESS OF CAST IRON PIPES FOR THE UNDERNOTED WORKING PRESSURE IN POUNDS PER SQUARE INCH.

Bore Diar. Ins.	Minimum thickness. Inches.	50 thickness. Inches.	100 thickness. Inches.	150 thickness. Inches.	200 thickness. Inches.	250 thickness. Inches.	300 thickness. Inches.	350 thickness. Inches.	400 thickness. Inches.
3	·250	·314	·326	·364	·385	·418	·452	·492	·531
4	·268	·332	·348	·390	·418	·457	·497	·545	·591
5	·286	·350	·370	·417	·451	·496	·542	·598	·625
6	·304	·368	·392	·443	·484	·536	·587	·651	·712
7	·322	·386	·414	·470	·517	·575	·633	·704	·773
8	·340	·404	·436	·497	·550	·614	·678	·756	·833
9	·358	·422	·458	·523	·583	·654	·723	·809	·893
10	·376	·440	·480	·550	·616	·693	·769	·862	·954
11	·394	·458	·501	·576	·650	·732	·814	·915	1·014
12	·412	·476	·523	·603	·683	·771	·859	·968	1·075
13	·430	·494	·545	·621	·716	·811	·905	1·021	1·135
14	·448	·512	·567	·656	·749	·850	·950	1·074	1·195
15	·466	·530	·589	·683	·782	·889	·995	1·127	1·256
16	·484	·548	·611	·709	·815	·929	1·041	1·180	1·316
18	·520	·584	·655	·763	·881	1·007	1·131	1·285	1·437
20	·556	·620	·698	·816	·947	1·086	1·222	1·391	1·558
21	·574	·638	·720	·842	·981	1·125	1·267	1·444	1·618
22	·592	·656	·742	·869	1·014	1·164	1·312	1·497	1·679
24	·628	·692	·786	·922	1·080	1·243	1·403	1·603	1·799
27	·682	·746	·852	1·002	1·179	1·361	1·539	1·762	1·980
30	·736	·800	·917	1·082	1·279	1·479	1·675	1·920	2·162
33	·790	·854	·983	1·162	1·378	1·597	1·811	2·079	2·343
36	·844	·908	1·049	1·241	1·477	1·715	1·946	2·238	2·524
42	·952	1·016	1·180	1·401	1·676	1·950	2·218	2·555	2·887
48	1·062	1·125	1·312	1·562	1·874	2·186	2·500	2·872	3·25

Table XV. the same dimensions in inches and fractions usually adopted in this country.

TABLE XIII.

THICKNESS OF CAST IRON PIPES FOR THE UNDERNOTED WORKING PRESSURE IN POUNDS PER SQUARE INCH.

Bore Diar. Inches.	Minimum thickness. Inches.	50 thickness. Inches.	100 thickness. Inches.	150 thickness. Inches.	200 thickness. Inches.	250 thickness. Inches.	300 thickness. Inches.	350 thickness. Inches.	400 thickness. Inches.
3	$\frac{1}{4}$	$\frac{5}{16}$	$\frac{5}{16}$ f	$\frac{3}{8}$ b	$\frac{3}{8}$ f	$\frac{13}{32}$	$\frac{7}{16}$ f	$\frac{1}{2}$	$\frac{17}{32}$
4	$\frac{5}{32}$	$\frac{21}{64}$	$\frac{11}{32}$	$\frac{3}{8}$ f	$\frac{13}{32}$	$\frac{7}{16}$ f	$\frac{1}{2}$	$\frac{9}{16}$ b	$\frac{19}{32}$
5	$\frac{9}{32}$	$\frac{11}{32}$	$\frac{3}{8}$	$\frac{13}{32}$	$\frac{7}{16}$ f	$\frac{1}{2}$	$\frac{9}{16}$ b	$\frac{19}{32}$	$\frac{5}{8}$
6	$\frac{9}{32}$ f	$\frac{11}{32}$ f	$\frac{25}{64}$	$\frac{7}{16}$	$\frac{1}{2}$ b	$\frac{17}{32}$	$\frac{19}{32}$	$\frac{21}{32}$	$\frac{11}{16}$ f
7	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{13}{32}$	$\frac{15}{32}$	$\frac{1}{2}$ f	$\frac{9}{16}$	$\frac{5}{8}$	$\frac{11}{16}$ f	$\frac{25}{32}$
8	$\frac{11}{32}$	$\frac{25}{64}$	$\frac{7}{16}$	$\frac{1}{2}$	$\frac{9}{16}$ b	$\frac{5}{8}$ b	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{27}{32}$
9	$\frac{3}{8}$ b	$\frac{13}{32}$	$\frac{15}{32}$	$\frac{1}{2}$ f	$\frac{19}{32}$	$\frac{21}{32}$	$\frac{23}{32}$	$\frac{13}{16}$	$\frac{7}{8}$ f
10	$\frac{3}{8}$	$\frac{7}{16}$ b	$\frac{1}{2}$ b	$\frac{9}{16}$ b	$\frac{5}{8}$ b	$\frac{11}{16}$	$\frac{25}{32}$	$\frac{7}{8}$ b	$\frac{15}{16}$ f
11	$\frac{3}{8}$ f	$\frac{7}{16}$ f	$\frac{1}{2}$	$\frac{9}{16}$	$\frac{21}{32}$	$\frac{3}{4}$ b	$\frac{13}{16}$	$\frac{29}{32}$	1 f
12	$\frac{13}{32}$	$\frac{15}{32}$	$\frac{16}{32}$	$\frac{9}{16}$ f	$\frac{11}{16}$	$\frac{25}{32}$	$\frac{7}{8}$ b	$\frac{31}{32}$	$1\frac{1}{16}$
13	$\frac{7}{16}$	$\frac{31}{64}$	$\frac{35}{64}$	$\frac{5}{8}$ b	$\frac{23}{32}$	$\frac{13}{16}$	$\frac{23}{32}$	1 f	$1\frac{1}{8}$
14	$\frac{7}{16}$ f	$\frac{1}{2}$	$\frac{9}{16}$	$\frac{21}{32}$	$\frac{3}{4}$	$\frac{27}{32}$	$\frac{15}{16}$ f	$1\frac{1}{16}$	$1\frac{3}{16}$
15	$\frac{15}{32}$	$\frac{33}{64}$	$\frac{19}{32}$	$\frac{11}{16}$	$\frac{25}{32}$	$\frac{7}{8}$ f	1	$1\frac{1}{8}$	$1\frac{1}{4}$
16	$\frac{1}{2}$	$\frac{17}{32}$	$\frac{39}{64}$	$\frac{23}{32}$	$\frac{13}{16}$	$\frac{15}{16}$	$1\frac{1}{32}$	$1\frac{3}{16}$	$1\frac{5}{16}$
18	$\frac{17}{32}$	$\frac{9}{16}$ f	$\frac{21}{32}$	$\frac{3}{4}$	$\frac{7}{8}$	1	$1\frac{1}{8}$	$1\frac{9}{32}$	$1\frac{7}{16}$
20	$\frac{9}{16}$	$\frac{5}{8}$	$\frac{23}{64}$	$\frac{13}{16}$	$\frac{15}{16}$	$1\frac{1}{16}$	$1\frac{7}{32}$	$1\frac{3}{8}$ f	$1\frac{9}{16}$
21	$\frac{9}{16}$ f	$\frac{5}{8}$ f	$\frac{23}{32}$	$\frac{27}{32}$	1 b	$1\frac{1}{8}$	$1\frac{1}{4}$	$1\frac{7}{16}$	$1\frac{5}{8}$
22	$\frac{19}{32}$	$\frac{21}{32}$	$\frac{3}{4}$ b	$\frac{7}{8}$ b	1 f	$1\frac{5}{32}$	$1\frac{5}{16}$	$1\frac{1}{2}$	$1\frac{11}{16}$
24	$\frac{5}{8}$	$\frac{11}{16}$	$\frac{51}{64}$	$\frac{15}{16}$ b	$1\frac{1}{16}$	$1\frac{1}{4}$	$1\frac{13}{32}$	$1\frac{19}{32}$	$1\frac{13}{16}$ b
27	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{27}{32}$ f	1	$1\frac{3}{16}$ b	$1\frac{3}{8}$ b	$1\frac{17}{32}$	$1\frac{3}{4}$	2 b
30	$\frac{3}{4}$ b	$\frac{13}{16}$ b	$\frac{63}{64}$	$1\frac{1}{16}$ f	$1\frac{9}{32}$	$1\frac{1}{2}$ b	$1\frac{11}{16}$	$1\frac{15}{16}$	$2\frac{5}{32}$
33	$\frac{25}{32}$	$\frac{7}{8}$ b	$\frac{31}{32}$	$1\frac{5}{32}$	$1\frac{3}{8}$	$1\frac{19}{32}$	$1\frac{13}{16}$	$2\frac{1}{16}$	$2\frac{11}{32}$
36	$\frac{27}{32}$	$\frac{7}{8}$ f	$1\frac{1}{32}$	$1\frac{1}{4}$	$1\frac{15}{32}$	$1\frac{23}{32}$	$1\frac{15}{16}$	$2\frac{1}{4}$ b	$2\frac{17}{32}$
42	$\frac{31}{32}$	1 f	$1\frac{3}{16}$	$1\frac{3}{8}$	$1\frac{11}{16}$	$1\frac{15}{16}$	$2\frac{7}{32}$	$2\frac{9}{16}$	$2\frac{7}{8}$
48	$1\frac{1}{16}$	$1\frac{1}{8}$	$1\frac{5}{16}$	$1\frac{9}{16}$	$1\frac{7}{8}$	$2\frac{3}{16}$	$2\frac{1}{2}$	$2\frac{7}{8}$	$3\frac{1}{4}$

Letter b signifies bare, letter f signifies full.

In Fig. VII. the dotted line shown gives the minimum thicknesses of metal practically possible for all sizes of cast

iron pipes from 2 to 48 inches diameter when cast vertically in dry sand moulds in lengths from 9 to 15 feet long, and tested in accordance with the usual specification for the best water-works practice. Pipes cast on a declivity, however, in greensand moulds, up to 6 inches diameter, are made even thinner ; but these are only used underground for the conveyance of gas at ordinary pressure for lighting, etc., in towns or cities, also as conductors for rain-water, drainage, and other such purposes in which the internal pressure is so low as to be of little importance. Under conditions otherwise normal, the thickness of metal derived from diagram Fig. VII., and detailed in Tables XII. and XIII., pp. 39 and 40, should not be reduced. In special cases, however, it may be advisable to meet the requirements by a corresponding increase in thickness. Such modifications must always be left to the discretion of the responsible engineer, who alone is familiar with the particular circumstances.

Generally speaking, continental engineers and cast iron pipe founders are satisfied with thicknesses from 10 to 15 per cent. less than is considered good practice by engineers in this country.

All cast iron pipes should be and usually are subjected to a hydraulic test at least twice the maximum working pressure when the working pressures and thicknesses are approximately in accordance with those given in Tables XII. and XIII., although a much higher test pressure may be applied with safety in special cases. They should also conform to reasonable tests for uniformity of thickness under the inspection and supervision of a specially qualified representative appointed by the engineer.

THICKNESS OF MILD STEEL PIPES.

Mild steel tubes and pipes of all diameters are either solid drawn from steel ingots or manufactured from steel strips and rolled sheets. The method of jointing employed in the latter and most extensive class consists either of welding or rivetting, the strength of which at the joint is considerably below that of the full section of plate at any other part of the shell.

In Table XV. are stated various methods of welding and rivetting employed in the manufacture of steel pipe, also the results of experiments carried out by Bertram, to ascertain the relative value of the different types by

TABLE XIV.

Description of Joint Section of Plate between Rivets 62·5 per cent. of Solid Plate.	Form of Joint. Test Pieces 4″ broad, 2¾″ diam. Rivets 2″ Pitch.	Ultimate strength of Joint; that of the entire Plate 100 per cent.			
		½ inch Plate.	7/16 inch Plate.	⅜ inch Plate.	Average.
		per cent.	per cent.	per cent.	per cent.
Entire plate - -		100	100	100	100
Scarf welded joint -		faulty	106	102	104
Lap ,, ,, (lap ¼″) -		50	69	66	62
Single rivetted by hand -		40	50	60	50
,, ,, snap heads -		50	52	56	53
,, ,, by machine -		40	54	52	49
,, ,, countersunk -		44	50	52	49
Double ,, snap heads -		59	70	72	67
,, ,, countersunk -		53	72	69	65
,, ,, sngl. butt strap		52	60	65	59

comparing the joint strength in each example with the strength of the plate away from the joint. In these tests Staffordshire plates were selected, the average tensile strength of which in the solid plate was 20 tons per square inch.

In each of these single rivetted joints the area of rivet section under shear was less than the corresponding net area of plate section in the line of rivets. The fracture, however, in nearly every case took place through the plate in the line of the rivets, and that, too, before the load per square inch had reached the amount equivalent to the ultimate tensile strength of the reduced area between the rivets, viz. 62·5 per cent. of the entire plate.

TABLE XV.

Description of Joint.	Thickness of Plate.	Diam. of Rivet.	Pitch of Rivet.	Breadth of Lap.	Percentage of Plate.	Percentage of Rivet.
					per cent.	per cent.
Entire plate	various	—	—	—	100	—
Lap welded	$\frac{1}{8}''$ to $\frac{1}{4}''$	—	—	—	68	—
,, ,,	$\frac{5}{16}''$ to $\frac{1}{2}''$	—	—	—	80	—
Single rivetted	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{2}{3}$	$\frac{3}{4}$	62·5	—
,, ,,	$\frac{3}{16}$	$\frac{3}{8}$	1	$1\frac{1}{8}$	62·5	—
,, ,,	$\frac{1}{4}$	$\frac{1}{2}$	$1\frac{1}{8}$	$1\frac{1}{2}$	56	69
,, ,,	$\frac{5}{16}$	$\frac{5}{8}$	$1\frac{1}{2}$	$1\frac{7}{8}$	58	65
,, ,,	$\frac{3}{8}$	$\frac{3}{4}$	$1\frac{3}{4}$	$2\frac{1}{4}$	57	67
,, ,,	$\frac{7}{16}$	$\frac{3}{4}$	$1\frac{3}{4}$	$2\frac{1}{4}$	57	58
,, ,,	$\frac{1}{2}$	$\frac{7}{8}$	$2\frac{1}{8}$	$2\frac{5}{8}$	58	56·7
Double ,,	$\frac{1}{2}$	$\frac{3}{4}$	$2\frac{1}{2}$	$3\frac{3}{4}$	70	70·6
,, ,,	$\frac{9}{16}$	$\frac{7}{8}$	3	$4\frac{1}{4}$	70	71·2
,, ,,	$\frac{5}{8}$	$\frac{7}{8}$	3	$4\frac{1}{4}$	70	64.0
,, ,,	$\frac{11}{16}$	1	3	$4\frac{1}{4}$	70	67·7
Treble ,,	$\frac{3}{4}$	$\frac{7}{8}$	$3\frac{1}{4}$	6	73·0	74·0
,, ,,	$\frac{13}{16}$	$\frac{15}{16}$	$3\frac{17}{16}$	$6\frac{3}{8}$	72·7	74·1
,, ,,	$\frac{7}{8}$	1	$3\frac{5}{8}$	$6\frac{3}{4}$	72·4	74·2
,, ,,	$\frac{15}{16}$	$1\frac{1}{16}$	$3\frac{7}{8}$	$7\frac{1}{8}$	72·5	73·2
,, ,,	1	$1\frac{1}{8}$	$4\frac{1}{8}$	$7\frac{5}{8}$	72·7	72·2

In very few instances in the tests did the joint fail by the shearing of a rivet.

The foregoing Table XV. gives the proportions of single, double and treble rivetted lap joints, and the corresponding reduction in effective area of plate between the rivets ; also the efficiency of the welded joint in a mild steel tube relative to the strength of the plate at other points of the shell, in accordance with the acknowledged practice of the best makers of welded steel pipe.

It has already been pointed out in page 37 that under all conditions of internal working pressure the thickness of cast iron pipes can be ascertained accurately with due regard to the necessary allowances suggested from practical experience, by using the fundamental formula (1) and introducing the factor F. It will be an advantage, therefore, to adopt as far as possible the same fundamental principle in calculating the thickness of steel pipe, viz. :

$$Pd = 2 \times t \times S \times 2240, \quad \ldots\ldots\ldots\ldots (1)$$

from which $$t'' = \frac{Pd}{2 \times t \times S \times 2240}.$$

With steel pipe it is in the first place necessary to take into account the loss of strength at the welded seams or rivetted joints as stated in Tables XIV. and XV. in order to arrive at the actual resistance to internal pressure. The factors of safety F and relative ultimate strength of any two pipes can then be readily ascertained by comparing the thickness adopted say for cast iron and mild steel pipes of the same diameters for the same working pressures with the theoretical thickness obtained by formula (1), as already stated on page 30.

The following rule has been used in general engineering work to ascertain the thickness of pipe, hollow cylinders,

boilers, and other cylindrical steel or iron structures subjected to internal fluid pressures, viz.:

$$\text{Thickness of shell } t \text{ inch} = \frac{D \times P}{F} + \tfrac{1}{8} \ldots\ldots\ldots\ldots (1)$$

The different values of F in this formula are stated below:

		Iron.	Steel.
Single rivetted lap joint	F =	11000	13700
Double ,, ,,	F =	14000	17500
Treble ,, ,,	F =	14500	18100

Example: A single rivetted steel pipe 24 inches diameter required to stand a working pressure of steam at 150 pounds per square inch is as follows:

Thickness of shell in inches

$$t = \frac{D \times P}{F} + \tfrac{1}{8} = \frac{24 \times 150}{13700} + \tfrac{1}{8}$$

$$= \cdot 2627 + \cdot 125 = \cdot 3877 \text{ inch} = \tfrac{3}{8} \text{ inch full.}$$

Thickness of shell for 130 lbs. per sq. in. working pressure

$$= \tfrac{3}{8} \text{ inch bare or } \tfrac{5}{16} \text{ inch full.}$$

The factor of safety provided for in this rule (1) relative to the strength of the entire plate forming the shell is readily ascertained by equating the thickness ·3877 inch with the fundamental formula (4), page 37, in which

$$t \text{ inch thick} = \frac{Pd \times \text{factor of safety F}}{2 \times S \times 2240} = \cdot 3877\,;$$

$$\therefore \text{ Factor of safety F} = \frac{\cdot 3877 \times 2 \times S \times 2240}{Pd}$$

$$= \frac{\cdot 3877 \times 2 \times 26 \times 2240}{150 \times 24}$$

$$= 12{\cdot}54 \text{ times.}$$

Taking into account the loss of strength in a single rivetted joint, the efficiency of which, stated in Tables XIV. and XV = 57 per cent.

$$\text{Factor of safety} \qquad F = \frac{12{\cdot}54 \times 57}{100} = 7{\cdot}1478 \text{ times.}$$

The factor of safety for double rivetted joints having an efficiency = 70 per cent., as stated in above Tables, is :

$$\therefore \text{ The true factor of safety } F = \frac{12{\cdot}54 \times 70}{100} = 8{\cdot}778 \text{ times.}$$

Again, take a lap welded steel tube 24 inches diameter for a working pressure of steam 150 pounds per square inch, the thickness of metal for which is

$$= {\cdot}4375 \text{ inch.}$$

The margin of strength ascertained as in the foregoing is as follows :

Factor of safety for full plate strength

$$F = \frac{{\cdot}4375 \times 2 \times S \times 2240}{Pd} = 14{\cdot}15 \text{ times.}$$

Taking the efficiency of lap welded joint = 68 per cent., the true factor of safety is

$$F = \frac{14{\cdot}15 \times 68}{100} = 9{\cdot}62 \text{ times.}$$

With an efficiency for lap welded joint = 80 per cent., the true factor of safety is

$$F = \frac{14{\cdot}15 \times 80}{100} = 11{\cdot}32 \text{ times.}$$

Table XVI. gives the thickness adopted as examples of cast iron and lap welded steel tubes from 6 to 24 inches diameter suitable for steam at a working pressure of 150 lbs. per square inch. The calculated factors F are added here to show the relative margins of safety for each size of pipe.

TABLE XVI.

Pipe Bore. Inches.	Lap Welded Steel Pipe.				Cast Iron Pipe.	
	Steam 150 lbs.		Water, 150 lbs.		Water, 133 lbs. per sq. in.	
	Thick-ness. Inches.	Factor of Safety F.	Thickness. Inches.	Factor of Safety F.	Thickness. Inches.	Factor of Safety F.
		Times.		Times.	Thick.	Times.
6 diar.	$\frac{1}{4}$	21	$\frac{1}{8}$	16·3	$\frac{7}{16}$	19·8
12 ,,	$\frac{5}{16}$	13·7	$\frac{3}{16}$	12·19	$\frac{5}{8}$	14·0
20 ,,	$\frac{3}{8}$	11·64	$\frac{1}{4}$	9·70	$\frac{7}{8}$	11·7
24 ,,	$\frac{7}{16}$	11·30	$\frac{5}{16}$	10·09	1	11·2
24 ,,	$\frac{3}{8}$	for 120 lbs. per sq. in. in working steam press. screwed flanges (heavy).				
24 ,,	$\frac{7}{16}$	for 200 lbs. per sq. in. welded flanges (medium).				
24 ,,	$\frac{5}{16}$	for 150 lbs. for water screwed or welded flanges (standard).				

Table XVII. gives the bursting pressures for welded steel pipe, taking into account the loss of strength along the welded joint.

Efficiency of weld up to $\frac{1}{4}''$ thick = 68 per cent. of the solid plate.

Efficiency of weld up to $\frac{5}{16}''$ thick and over = 80 per cent. of the solid plate.

As shown in Table XV., page 43, for welded and rivetted joints.

For steel having an ultimate tensile strength = 26 tons per sq. in. the bursting strength of a pipe along the welded joint therefore varies with the thickness from 18 to 21 tons per sq. in.

As representing the usual practice, steel pipe makers have recommended that the

Test-pressure should not exceed one-third bursting pressure,

Working pressure for water should not exceed one-fourth bursting pressure,

Working pressure for steam should not exceed one-tenth bursting pressure.

TABLE XVII.

BURSTING PRESSURES IN POUNDS PER SQUARE INCH.

Bore in inches.	Thickness in inches.					
	$\frac{3}{16}$	$\frac{1}{4}$	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{7}{16}$	$\frac{1}{2}$
10	1485	1980	2912	3494	—	—
11	1350	1800	2647	3177	3706	—
12	1237	1650	2427	2912	3398	3883
13	1142	1523	2240	2688	3136	3584
14	1061	1415	2080	2496	2912	3328
15	990	1320	1941	2329	2718	3106
16	928	1237	1820	2184	2548	2912
17	—	1165	1713	2055	2398	2741
18	—	1100	1618	1941	2265	2588
19	—	1042	1533	1839	2146	2452
20	—	990	1456	1747	2038	2330
21	—	943	1387	1664	1941	2219
22	—	900	1324	1588	1853	2118
23	—	—	1266	1519	1772	2026
24	—	—	1213	1456	1698	1941
27	—	—	—	—	1510	1726
30	—	—	—	—	—	1553

In Table XVI., page 47, the margin of strength provided in cast iron pipe is greater than that for lap welded steel pipe to the extent of from 10 to 20 per cent. If, however, the ratios of working to bursting pressures recommended by leading steel pipe makers, as stated in the foregoing, are adopted, the thicknesses would be still less than those stated in Table XVI. for water at 150 lbs. per square inch, and the factor of safety correspondingly reduced.

Taking into consideration the effect of reduced thickness in determining the useful life of a pipe under the influence of corrosive action, and also the smaller margin of strength in steel pipes compared with that of cast iron pipes, the adoption of steel in many cases would seem to be doubtful economy.

Take, for example, the 30 inch diameter steel pipe $\frac{1}{4}''$ thick adopted in the Coolgardie Scheme, Western Australia, for a working pressure of 169 lbs. per square inch.

$$\text{The factor of safety} = \frac{\cdot 25 \text{ inch thick}}{\cdot 039 \text{ theo}^{1} \text{ thickness}} = 6 \cdot 41.$$

Take again a 30 inch cast iron pipe for the same working pressure, by referring to Tables XII. and XIII., pages 39 and 40, the thickness of metal would be $1\frac{3}{16}$ inch, from which the factor of safety = 8,

$$\therefore \frac{\text{factor (F) for cast iron pipe}}{\text{factor (F) for steel pipe}} = \frac{8}{6 \cdot 41} = \frac{124 \cdot 8}{100}.$$

From this example the cast iron pipe comes out at practically 25 per cent. stronger than the steel pipe under the same conditions of working pressure, *i.e.* the cast iron pipe might be reduced from $1\frac{3}{16}$ to $\frac{15}{16}$ inch thick in order to bring both steel and cast iron pipes on equal terms as regards their resistance to bursting pressure, and thus a corresponding reduction on the initial cost of such a cast iron pipe scheme.

STRENGTH OF PIPES AND HOLLOW CYLINDERS UNDER EXTERNAL LOAD.

In the construction of sewers and other water ways underground, in which the rate of flow is maintained by the fall or gradient as in open channels, the arched work and proportions adopted give evidence of the greatest care and appreciation of the nature and extent of the external loads to which such structures are subjected and must be capable of carrying without danger of collapse. In the case of underground pipes carrying water under pressure, the thickness of the tube structure is usually considered with regard only to internal working pressure and the strength to resist bursting. The thickness of cast iron pipe derived in this way is, however, generally considerably more than sufficient to carry any external load under ordinary working conditions when the pipe is empty and unsupported from within by hydraulic pressure, and even should a partial vacuum be formed as in the case of an excessive discharge at some low-lying point on the line of pipe, to avoid which automatic air inlet valves are usually provided. When the ratio of thickness to the diameter of pipe is low, as in the case of steel compared to that of cast iron pipe, the importance of considering the strength of such a pipe with due regard to possible external loads becomes more apparent.

In Table XVIII. are given the relative bursting and

collapsing pressures for small bore solid drawn wrought iron tubes up to 6 inches diameter. These figures show that the resistance to collapse is not only less than that under internal pressure throughout, but that it diminishes more rapidly with the increase in diameter.

The strength of these small tubes to resist collapse is given in terms of pressure, diameter and thickness as follows, viz.:

$$P = t'' \times \left(\frac{112000}{D} - 12000\right) \ldots\ldots\ldots\ldots (1)$$

P = External Pressure in pounds per square inch.

D = ,, Diameter in inches.

t = thickness of Metal in inches.

*TABLE XVIII.

External Diameter.	Thick-ness.	BURSTING PRESSURE.		COLLAPSING PRESSURE.	
		Internal Pressure per sq. in.	Direct Tension. $\left(\frac{P \times D}{2t}\right)$ per sq. in.	External Pressure per sq. in.	Direct Compression. $\left(\frac{P \times D}{2t}\right)$ per sq. in.
$1\frac{1}{4}$ ins.	·083	7700 lbs.	22·4 tons	6500 lbs.	21·7 tons
2 ,,	·083	4500 ,,	22·4 ,,	3700 ,,	19·7 ,,
3 ,,	·120	4400 ,,	22·4 ,,	3000 ,,	17·0 ,,
4 ,,	·134	3600 ,,	22·4 ,,	2100 ,,	14·3 ,,
5 ,,	·134	2800 ,,	22·4 ,,	1400 ,,	11·7 ,,
6 ,,	·148	2600 ,,	22·4 ,,	1000 ,,	9·0 ,,

In order to determine the strength of any size of pipe or hollow cylindrical structure under a uniform external load, tending to produce collapse, specially conducted tests have been carried out on tubes of various diameters under gradually increasing external loads produced by

* D. K. Clark's *Rules and Tables.*

means of hydraulic pressure up to the point of collapse; valuable data have also been derived from an analysis of failures by collapse of boiler furnace tubes, etc. The relations existing between uniform external pressure and stresses produced in the material forming the shell have also been determined mathematically, and rational formulae derived which show that the critical collapsing pressure can be estimated with reasonable accuracy and in accordance with the latest experience and tests such as those referred to.

Two formulae (1) and (2) have been derived from careful mathematical analysis of results from tests of thin and thick tubes respectively as follows: *

Love's Formula for Thin Tubes.

$$P = \frac{2E}{1-M^2}\left(\frac{t'}{R}\right)^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

P = Collapsing Pressure in pounds per square inch.

E = Young's Modulus of Elasticity.

M = Poisson's Ratio of Lateral to transverse deformation.

t' = half thickness of metal in inches.

R = Mean Radius of Pipe " "

Lame's Formula for Thick Tubes.

$$P = \frac{Wc\,(R^2-r^2)}{2R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

P = Collapsing Pressure in pounds per square inch.

Wc = Ultimate Compressive Strength of metal.

R = External Radius of Pipe in inches.

r = Internal " " "

* See *Engineering*, 8th January, 1909.

VALUES FOR DIFFERENT FACTORS.

E for Steel	- -	= 30,000,000	pounds	per	sq. in.
E ,, Cast iron	- -	= 12,000,000	,,	,,	,,
Wc ,, Steel	- -	= 40,000	,,	,,	,,
Wc ,, Cast Iron	- -	= 95,000	,,	,,	,,
M ,, Steel	- -	= 000·295		,,	,,

In order to compare formulae (1) and (2) the different factors will be more convenient when reduced to similar terms as follows, viz.:

t = thickness of metal in shell in inches.

D = diameter (internal) of ,, ,,

By Love's formula (1) for thin pipe—

$$P = \frac{2E}{1-M^2}\left(\frac{t'}{R}\right)^3 = \frac{2E}{1-M^2}\left(\frac{t}{D}\right)^3;$$

$$\therefore \text{ P (for steel pipe)} = \frac{2\times 30{,}000{,}000}{1-{\cdot}295^2}\left(\frac{t}{D}\right)^3$$

$$= 65{,}720{,}000\left(\frac{t}{D}\right)^3.$$

By Lame's formula (2) for thick pipe—

$$P = \frac{Wc\,(R^2-r^2)}{2R^2} = Wc\left(\frac{t}{R}-\frac{t^2}{2R^2}\right)$$

$$= 2Wc\left(\frac{t}{D}-\left(\frac{t}{D}\right)^2\right);$$

$$\therefore \text{ P (for steel pipe)} = 80{,}000\left(\frac{t}{D}-\left(\frac{t}{D}\right)^2\right),$$

$$\therefore \text{ P (for cast iron pipe)} = 190{,}000\left(\frac{t}{D}-\left(\frac{t}{D}\right)^2\right).$$

The relative values derived from these foregoing formulae (1) and (2) are graphically shown by the different curves in Fig. VIII. The vertical ordinates repre-

senting the critical pressure P in pounds per square inch, and the abscissae or horizontal dimensions representing the different ratios $\frac{t}{D}$. These theoretical dotted curves, obtained for thin and thick tubes respectively, it

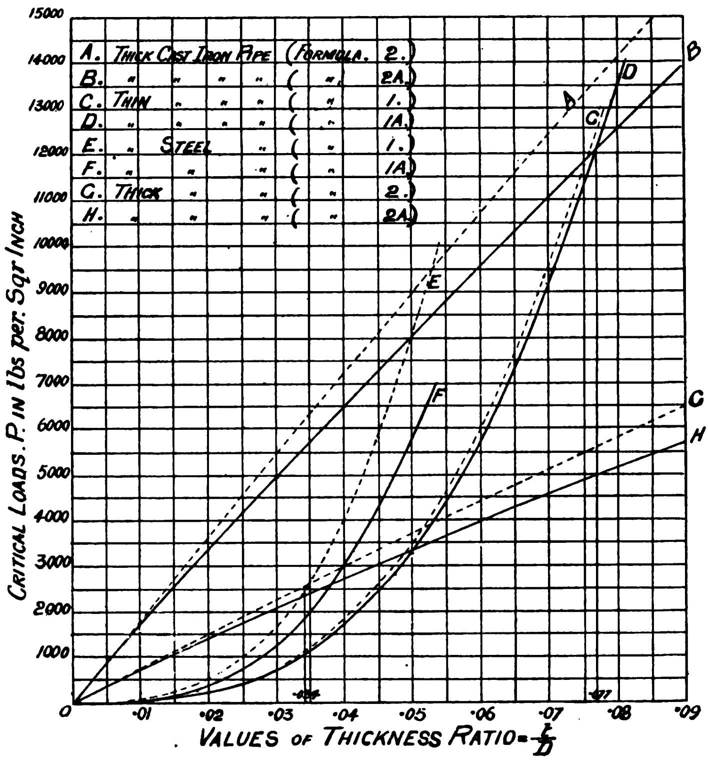


FIG. VIII.

will be seen, cross each other at a point corresponding to the ratio $\frac{t}{D} = \cdot 034$. This indicates that formula (1) for thin tube should be used for ratios $\frac{t}{D}$ below ·034 and formula (2) for thick tubes having a ratio beyond that value.

In addition to the foregoing theoretical considerations for thin tubes it is necessary to take into account variations in form and thickness, as the critical pressure P varies directly as the thickness cubed (t^3) and indirectly as the diameter cubed (D^3). The values for such variations in practice, derived from careful measurements of the series of tubes tested, are represented by the following correcting factors :

$C_1 = \left(\frac{d}{D}\right)^3$ = 96·7 per cent. = Correction for Ellipticity in thin tubes.

$C_2 = \left(\frac{t \text{ min.}}{t \text{ average}}\right)^3$ = 71·2 per cent. = Correction for thickness variation.

$C = C_1 \times C_2$ = 69·0 per cent. = Correction for Ellipticity and thickness.

Formula (1), page 52, with the necessary correction then becomes

$$P = C \times \frac{2E}{1 - M^2} \left(\frac{t}{D}\right)^3.$$

C = 69 per cent. for lap welded thin steel tubes,

and = 76 per cent. for seamless solid drawn thin steel tubes.

D = maximum outside diameter in inches.

t = Average thickness in inches.

In applying formula (2) for thick tubes, it is also necessary as in the foregoing to introduce correction factors for variations in form, and thickness of ordinary commercial tubes, as follows, viz. :

$C_1 = \frac{d}{D}$ = ·9874 = Factor for Ellipticity in thick tubes.

$$C_2 = \frac{t \text{ min.}}{t \text{ average}} = \cdot 9022 = \text{Factor for thickness variation in thick tubes.}$$

$$\therefore C = C_1 \times C_2 = \cdot 89 = \text{Factor for } \textit{Ellipticity} \text{ and thickness.}$$

$$\frac{D^2}{d} = \text{Equivalent diameter} = 2 \times \text{Radius of curvature at the flattest portion of the tube.}$$

The correction in formula (2) for thick tubes including ellipticity and variation in thickness works out as follows :

$$P = Wc \frac{(R^2 - r^2)}{2R^2} = 2Wc\left(\frac{t}{D} - \left(\frac{t}{D}\right)^2\right).$$

$$\text{Substituting } \frac{D^2}{d} \text{ for } D = 2Wc\left(\frac{td}{D^2} - \left(\frac{td}{D^2}\right)^2\right)$$

$$\left.\begin{array}{l}\text{Substituting } C_1 \text{ for } \dfrac{d}{D} \\ \qquad\qquad C_2 t \text{ ,, } t\end{array}\right\} = 2Wc\, C_1 \frac{C_2 t}{D}\left(1 - C_1 \frac{C_2 t}{D_1}\right)$$

$$= 2Wc\, C \frac{t}{D}\left(1 - C\frac{t}{D}\right)$$

$$\therefore P = 2Wc\, 0{\cdot}89 \frac{t}{D}\left(1 - 0{\cdot}89\frac{t}{D}\right).$$

From the rational analysis of Love and Lame expressed in formulae (1) and (2), when supplemented by other factors derived from experimental data, we obtain the two following formulae 1A and 1B, including the correcting factors referred to. The critical collapsing pressures can thus be estimated with reasonable accuracy and in accordance with the results of tests referred to.

(*a*) For *thin welded steel tubes*

$$P = 0{\cdot}69 \times \frac{2E}{1 - M^2}\left(\frac{t}{D}\right)^3. \quad \ldots\ldots\ldots\ldots (1\text{A})$$

$$\left(\text{Ratio } \frac{t}{D} \text{ less than } \cdot 034\right) = 45346800\left(\frac{t}{D}\right)^3.$$

(*b*) For *thin cast iron pipes*

$$P = 26286966 \left(\frac{t}{D}\right)^3 \text{ .... (1A)}$$

$$\left(\text{Ratio } \frac{t}{D} = \cdot 08\right).$$

(*c*) For *thick welded steel tubes*

$$P = 2\text{Wc } 0{\cdot}89 \frac{t}{D}\left(1 - 0{\cdot}89 \frac{t}{D}\right). \text{ .. (2A)}$$

$$P = 71{,}200 \frac{t}{D}\left(1 - 0{\cdot}89 \frac{t}{D}\right).$$

(*d*) For *thick cast iron pipe*

$$P = 169{,}100 \frac{t}{D}\left(1 - 0{\cdot}89 \frac{t}{D}\right). \text{ ... (2A)}$$

$$\left(\text{Ratio } \frac{t}{D} = \cdot 08\right).$$

The dotted line curves, compared to those in full lines in Fig. VIII., show the relative critical collapsing pressures P for different ratios $\frac{t}{D}$ plotted from the results obtained by the formulae 1 and 1A, also 2 and 2A, for steel and cast iron tubes, taking into account the variations in form and thickness in accordance with the usual practice. In constructing the curve for cast iron pipe it has been assumed that the variations in form and thickness are the same as for lap welded steel tubes.

By means of these curves the critical collapsing pressures for cast iron and lap welded steel tubes of the same diameters are clearly shown by reference to the ratios $\frac{t}{D}$ representing in each case their relative values in accordance with the usual practice for pipes constructed of these two materials for the same working pressures.

The following Table XIX. gives the results as ascer-

tained from the diagram Fig. VIII. and formula 1A, for the different diameters stated.

FOR WORKING PRESSURE 150 POUNDS PER SQUARE INCH.

TABLE XIX.

	Lap Welded Steel Pipe.			Cast Iron Pipe.		
Diar. Inches.	Thickness. Inches.	Thickness Ratio $\frac{t}{D}$	Collapsing Pressure. Pounds per sq. in.	Thickness. Inches.	Thickness Ratio $\frac{t}{D}$	Collapsing Pressure. Pounds per sq. in.
			(1A)			(1A)
12	$\frac{3}{16}$ =·187	·0155	168·871	$\frac{9}{16}$ = ·603	·0502	3285·87
24	$\frac{1}{4}$ =·250	·0104	51·015	$\frac{15}{16}$ = ·922	·0384	1445·78
30	$\frac{5}{16}$ =·312	·0104	51·015	$1\frac{1}{16}$ =1·082	·0360	1314·35
36	$\frac{3}{8}$ =·375	·0104	51·015	$1\frac{1}{4}$ =1·241	·0344	1025·19
42	$\frac{7}{16}$ =·437	·0104	51·015	$1\frac{3}{8}$ =1·401	·0333	946·83
48	$\frac{1}{2}$ =·500	·0104	51·015	$1\frac{9}{16}$ =1·562	·0325	902·43

It will thus be seen that when considered with regard to resistance under the most favourable conditions of a uniform external pressure tending to produce collapse, cast iron pipes are much stronger than welded steel pipes of the relative thicknesses usually adopted for the same working pressures.

It should be here noted that the limiting ratio $\frac{t}{D}$ = ·077 for cast iron pipe 12 to 36 inches diameter is higher than that for welded steel pipe. The thin tube formula (1A), is therefore used for cast iron pipe, when the limiting ratio $\frac{t}{D}$ does not exceed ·077, *i.e.* the point where the curves from formula (1A) and (2A) cut or intersect each other. For ratios higher than $\frac{t}{D}$ = ·077 the collapsing pressure P is estimated by using Lame's formula (2A) for thick tubes.

In this connection it is interesting to examine the following formula (3) and the collapsing pressures determined by it, as it affords independent evidence of the accuracy of the results obtained by the foregoing rational formula (1A). Formula (3) is essentially empirical and is derived from careful analysis of 21 cases of failure in Lancashire and Cornish Boilers due to collapse of furnace tubes from 32 to 48 inches diameter, $\frac{3}{8}$ to $\frac{7}{16}$ inch thick, and 18 to 40 feet long. Within the limits stated the length of tube was found to be the least important factor, so that it has not been included in this formula.

The factors used are as follows :

P = Collapsing external pressure in pounds per sq. in.
D = Internal diameter of tube in inches.
t = Thickness of plate in inches.
L = Length of tube unsupported in feet.

$$P = \frac{200{,}000 \times t^2}{D^{1 \cdot 75}} \quad \ldots \ldots \ldots \ldots (3)$$

Examples—

(*a*) A steel pipe 30 in. diameter, $\frac{1}{4}$ in. thick, 40 feet long, with fixed ends.

Pounds per sq. in.

$$P = \frac{200{,}000 \times \cdot 25^2}{30^{1 \cdot 75}} = 32 \cdot 5 \quad \ldots \ldots \ldots (3)$$

$= 37 \cdot 59$ by Love's formula for steel. .(1A)

(*b*) A steel pipe 36 in. diameter, $\frac{5}{16}$ in. thick, 40 feet long, with fixed ends.

$$P = 36 \cdot 83 \text{ pounds per sq. inch.} \quad \ldots \ldots (3)$$

(*c*) A steel pipe 36 in. diameter, $\frac{3}{8}$ in. thick, 40 feet long, with fixed ends.

$$P = 53 \cdot 05 \text{ pounds per sq. inch.} \quad \ldots \ldots (3)$$

The direct compressive stress (Wc′) as represented by

$$Wc' = \frac{P \times D}{2t} \begin{cases} (a) & = \cdot 87 \text{ tons per sq. inch.} \\ (b) & = \cdot 94 \quad ,, \quad ,, \\ (c) & = 1{\cdot}13 \quad ,, \quad ,, \end{cases}$$

The total distributed loads (L) equivalent to the various critical pressures on these 12 feet lengths of pipe, as stated, equals

$$L = \frac{P \times D \times 144 \text{ in.}}{2240} = \begin{cases} (a) & = 62{\cdot}6 \text{ tons.} \\ (b) & = 85{\cdot}0 \quad ,, \\ (c) & = 122{\cdot}5 \quad ,, \end{cases}$$

These examples show that failure by collapse is due to the comparative weakness of a thin steel arch to resist an external transverse load while the direct compression stress is still very low.

For tubes 18 feet long and under between fixed ends, or when strengthened by specially designed stiffening rings at short intervals, the strength under a uniform external load tending to collapse increases as the length of tube or the distance between the stiffening rings is diminished.

Take for instance the result of testing a wrought iron * furnace tube 37 inches diameter inside, $\frac{3}{8}$ inch thick, 7 feet long, under an external hydraulic pressure. This gave way by collapse at a pressure of 175 pounds per square inch.

By the foregoing formula for long tubes.

$$P = \frac{200{,}000 \times \cdot 375^2}{37^{1 \cdot 75}} = 50{\cdot}66 \text{ pounds per square inch.}$$

By actual test on short tube 7 feet long.

P = 175 lbs.

= 3·45 times that of a similar tube 40 feet long.

* See D. K. Clark's *Rules and Tables*.

Direct comprehensive stress for this example is

$$Wc' = \frac{P' \times D}{2t} = 3{\cdot}8 \text{ tons per square inch.}$$

The external loading to which an underground pipe is subjected may be estimated as follows:

Weight of soil covering a pipe 36 inches diameter, 12 feet long, of 6 feet average depth, say - - - - -	= 15·0 tons.
Weight due to traffic overhead, say - -	= 15·0 ,,
∴ Total estimated distributed load	= 30·0 ,,

In the foregoing example (*b*), page 59, the calculated pressure by formula (3) at which a 36 in. diameter steel pipe $\frac{5}{16}$ in. thick will fail by collapse is $P = 36{\cdot}83$ pounds per square inch. Therefore the total pressure or distributed load on the surface of a pipe 36 inch diameter, 12 feet long, tending to produce collapse is $= P \times D \times L$.

$= 36{\cdot}83 \times 36 \times 144.$

$= 190{,}926{\cdot}72$ pounds.

$= 85{\cdot}2$ tons.

which shows a margin of strength when the pipe is empty and under an external load of 30 tons, as detailed above $= \dfrac{85{\cdot}2}{30} = 2{\cdot}84$ times.

Do. do. due to weight of soil only $= 5{\cdot}68$ times.

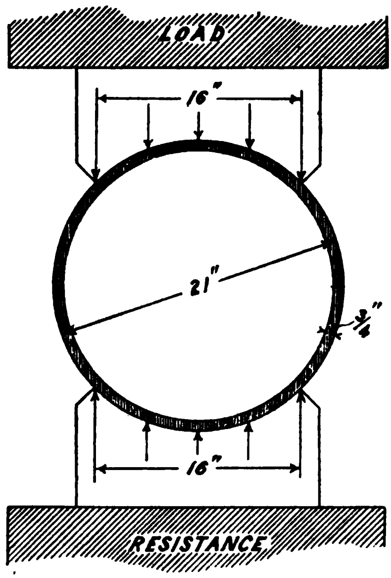
In these circumstances the margin of safety is obviously too low.

TESTS ON CAST IRON PIPES UNDER EXTERNAL LOADS.

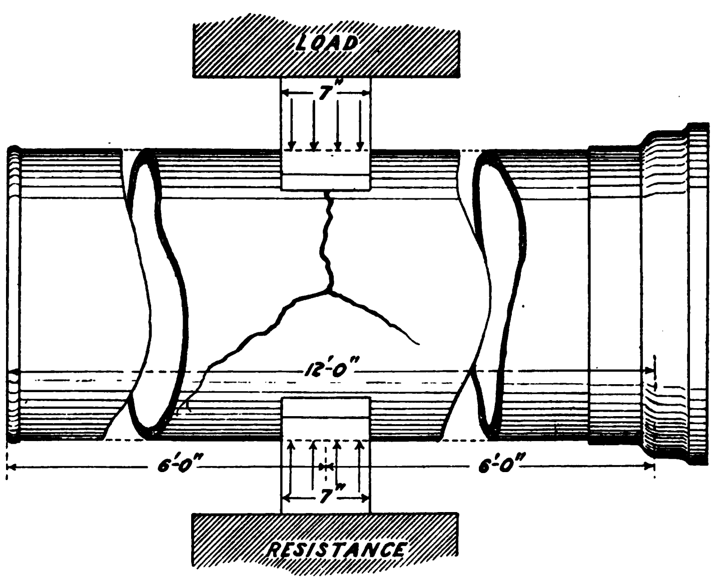
A number of cast iron pipes were tested under external loads, owing to the breaking of an underground cast iron water main, due, it was considered, to an excessive load on the street immediately over the track, during the process of erecting the main girders of a railway bridge. Questions arose which led to the following experiments being carried out by the writer to ascertain in a simple and practical manner the strength of cast iron pipes of ordinary thickness when subjected to direct external loads.

The test loads were applied as shown in the various illustrations by means of hydraulic pressure acting on a ram 18 inches diameter, the effective load being estimated after deducting 10 per cent. for frictional losses, from the pressures indicated on a gauge connected to the hydraulic cylinder. Fig. IX. represents a cast iron pipe 21 inches diameter, $\frac{3}{4}$ inch thick, 12 feet long, with the load applied at the centre of its length through bearing blocks on opposite sides, each with a bearing surface one-fourth of the circumference and 7 inches long. The pressure was applied gradually and reached the maximum with a sharp sound and fracture represented by the lines shown.

Maximum breaking load -	=	51 tons.
Area of bearing surface 16×7	=	112 square inches.
Pressure on ,, ,, ,,	=	1020·5 lbs. p. sq. in.



END ELEVATION



SIDE ELEVATION

Fig. IX.

(*a*) The same pipe was again tested with the bearing blocks placed so that the test load was applied at 24 inches from the spigot end where the pipe is weakest.

Maximum breaking load -	=	35·7 tons.
Area of bearing surface -	=	112 square inches.
Pressure on ,, -	=	714 lbs. per sq. in.

Three rings were cut from a pipe 21 inches diameter of different thicknesses, viz., $\frac{3}{4}''$, $\frac{7}{8}''$, and $\frac{15}{16}''$ thick, and tested under loads applied as shown in Fig. X.

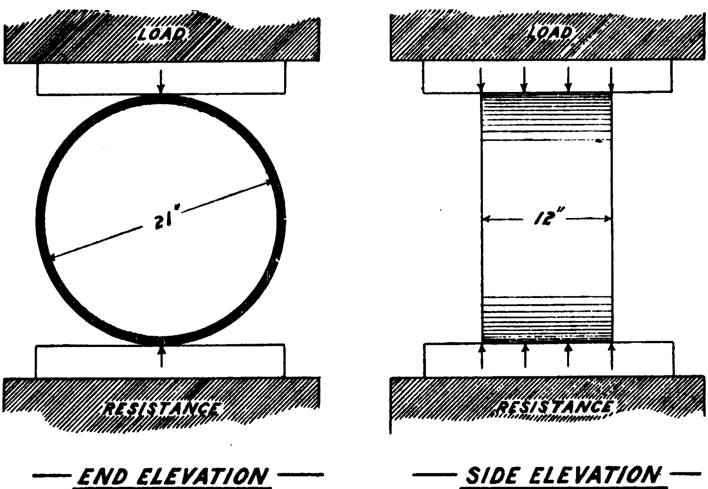


Fig. X.

(*a*) Cast iron ring 21 in. diameter, $\frac{3}{4}$ in. thick, 12 in. long.

Maximum breaking load - = 7·37 tons.

,, ,, on line of contact = 1375 lbs. per lin. in.

(*b*) Cast iron ring 21 in. diameter, $\frac{7}{8}$ in. thick, 12 in. long.

Maximum breaking load - = 8·5 tons.

,, ,, on line of contact = 1587 lbs. per lin. in.

(*c*) Cast iron ring, 21 in. diameter, $\frac{15}{16}$ in. thick, 12 in. long.

Maximum breaking load.
Approximately the same as in test (*b*).

A series of three tests was also carried out on a cast iron pipe 21 inch diameter, $\frac{7}{8}$ inch thick, 12 feet long, the load being concentrated by transmitting it through a flat bar 1 inch broad as shown at (*A*), (*B*) and (*C*) Fig. XI.

Pipe 21 *inch diameter.*

(*A*)	Maximum concentrated load producing fracture when applied at	24 inch from spigot -	=	14·74 tons.
(*B*)	Do. do.	72 inch from spigot -	=	15·8 ,,
(*C*)	Do. do.	26 inch from socket -	=	17·0 ,,

Pipe 12 *inch diameter.*

A 12 in. diameter cast iron pipe $\frac{5}{8}$ in. thick metal was also tested as in the foregoing example at (*A*), (*B*) and (*C*), Fig. XI.

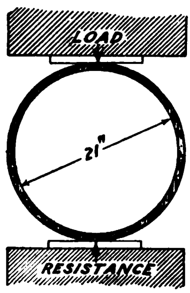
(*A*)	Maximum concentrated load producing fracture when applied at	24 inch from spigot -	=	10 tons.
(*B*)	Do. do.	72 inch from spigot -	=	11·3 ,,
(*C*)	Do. do.	26 inch from socket -	=	10 ,,

A cast iron pipe 21 in. diameter, $\frac{3}{4}$ in. thick, 12 feet long was also tested in order to show the effect on the strength under a collapsing or crushing load by increasing the length of the line of contact.

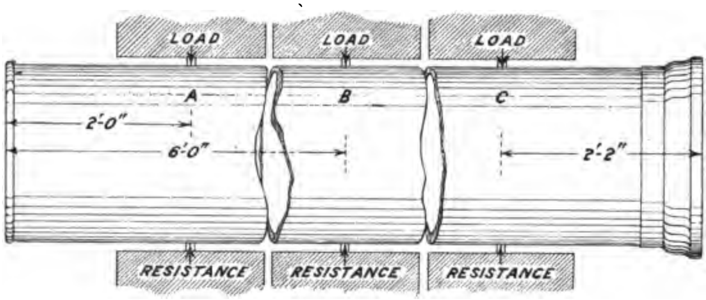
(*a*) The bearing line of contact was metal to metal; the load was therefore not absolutely uniform along the rough cast surface.

Maximum load producing fracture

= 20·4 tons = 1063 lbs. per lineal inch.



END ELEVATION



SIDE ELEVATION

FIG. XI.

(a^1) The same test as (*a*) on a 21 inch pipe, $\frac{3}{4}$ in. thick, except that a sheet of paste-board $\frac{1}{8}$ inch thick was placed between the bearing surfaces in order to ensure a more perfect distribution of the load along the line of contact.

Maximum load producing fracture

= 26·08 tons = 1376 lbs. per lin. inch.

Abstract of the foregoing results of Tests.

Description.	Crushing Load producing Fracture.		
	(A)	(B)	(C)
Cast iron pipe, 21 inch dia., $\frac{3}{4}''$ thick, loaded as shown in Fig. IX., 24″ from spigot	35·7 tons	51 tons	
Do., 21 inch dia., $\frac{3}{4}''$ thick, loaded on a line 43 inch long, as shown in Fig. X. -	26·08 ,,	—	—
Do., 21 inch dia., $\frac{7}{8}''$ thick, with concentrated load as shown in Fig. XI. - -	14·74 ,,	15·8 ,,	17·0 tons
Do., 12 inch dia., $\frac{5}{8}''$ thick, with concentrated load, Fig. XI. - - - -	10.00 ,,	10·0 ,,	11·3 ,,
Do., Ring 21 inch dia., $\frac{3}{4}''$ thick, loaded as in Fig. X. - - - -	7·37 ,,	—	—
Do., $\frac{7}{8}''$ thick - -	8·50 ,,	—	—

The external loads to which an underground pipe main may be subjected, for example heavy traffic passing over its track, are not usually uniformly distributed over the surface, but will be more or less concentrated, depending on the nature of the subsoil, also that of the soil forming the cover. As indicating the effect of external loading it has been stated that steel pipe from 36 to 72 inches diameter and $\frac{1}{4}$ to $\frac{1}{2}$ inch thick with a cover of 6 to 8 feet, collapse when empty, to such an extent that the normal vertical diameter is reduced by 10 per cent., and the horizontal diameter increased correspondingly. This, however, will depend on whether or not the pipe is properly laid and the soil carefully rammed all round to form a uniform support. Carelessness in the laying of a pipe

where the structure of the subsoil is variable, containing stones and boulders, may lead to serious results when the pipe bears down hard on such boulders, as the pipe then becomes like a beam structure carrying a transverse load due to the weight of water inside its own weight of metal, and the overhead weight of soil within the distance corresponding to the span or length between the points of support. The danger of collapse is increased by the removal of the support from internal hydraulic pressure, and also in the event of a partial vacuum being formed inside, as already pointed out in page 50.

Should such irregularities occur when a pipe is laid, due to local subsidence of the subsoil or otherwise, the comparatively thin steel pipe may thus be subjected to stresses which produce collapse, while a cast iron pipe by its greater thickness and corresponding increase in strength would, under the same conditions, remain unimpaired. When subsidence takes place along the pipe track for a considerable distance, the greater number of spigot and socket joints in the cast iron pipe main has been found to give a considerable amount of flexibility which enables it to better accommodate itself like a chain to the altered conditions without serious results. In the case of a steel main with fewer joints, or when rivetted up so as to form a continuous line, such subsidence may throw a dangerous stress at the rivetted joints, with consequent leakage, and in extreme cases rupture of the plate or shearing of rivets takes place.

In a report by A. Haufmann, Gas Manager, he states that owing to the bending of a steel pipe gas main the joints became leaky so that water from outside found its way into the interior and collected at the lowest points or cavities formed by bending, to such an extent that

openings for branch service pipes were covered with water and the supply of gas thus cut off.

Bearing on this point, an important and interesting example of flexibility is reported with reference to a 30 inch diameter cast iron pipe line at Eighth Avenue, New York, which was lifted 8 feet out of its trench, a distance of half a mile, and shifted to one side, while the water was flowing through. The street grade was raised and the pipe slipped back again without once shutting off the water. Apart from examples of this kind, experience has shown to advantage the number of joints employed in cast iron piping, and also that it is possible to have a considerable amount of deflection in the line of such piping in the event of subsidence referred to without serious leakage taking place. The greater number of joints also allows a certain amount of telescopic action necessary for the free expansion and contraction throughout the line of piping, due to variations in temperature, without excessive stress and leakage, which in the case of a rivetted steel main might cause considerable damage through excessive stress and consequent leakage at the joints.

Should subsidence take place to such an extent that the pipe becomes practically suspended between two points of support, like a beam carrying a load either concentrated or distributed, the strength of a pipe thus suspended and subjected to bending is represented by the following formula :

Bending Moment, due to concentrated load

$$\frac{WL}{4} = \frac{\text{Area of pipe section}}{2} \times \frac{D}{2} \times S$$

$$= \frac{3{\cdot}1416 \times D \times t}{2} \times \frac{D}{2} \times S$$

$$= {\cdot}7854D^2t \times S\,;$$

∴ Concentrated breaking load in tons

$$W = \frac{\cdot 7854 D^2 t}{L} \times 4.S$$

$$= \frac{3 \cdot 1416 D^2 t}{L} \times S \text{ in tons.}$$

To determine the relative strength of any two pipes of the same diameter under the foregoing conditions the only factors in the formula that vary when different metals are employed are the annular area of section and the value of S (the maximum tensile strength of the metal), and as the annular areas of section are in direct proportion to the thickness of metal, the relative strength of a 36 inch diameter cast iron pipe $1\frac{3}{8}$ inch thick and that of a 36 inch diameter steel pipe $\frac{3}{8}$ inch thick for the same internal pressure is represented as follows :

S = Ultimate tensile strength in tons per sq. inch.
L = Length of span in inches.
D = Diameter in inches.
t = Thickness in inches.

$$\frac{\text{Strength of } 36'' \text{ diar. C.I. pipe } 1\tfrac{3}{8}'' \text{ thick}}{\text{,, } \quad 36'' \text{ ,, M.S. ,, } \tfrac{3}{8}'' \text{ ,,}}$$

$$= \frac{1 \cdot 375 \times 8 \text{ tons per sq. in.}}{\cdot 375 \times 26 \quad \text{,,} \qquad \text{,,}} = \frac{11}{9 \cdot 75} = \frac{100}{88 \cdot 6}.$$

$$\frac{\text{Strength of } 36'' \text{ diar. C.I. pipe } 1\tfrac{3}{8}'' \text{ thick}}{\text{,, } \quad 36'' \text{ ,, M.S. ,, } \tfrac{5}{16}'' \text{ ,,}} = \frac{100}{73 \cdot 8}.$$

So that the cast iron pipe, owing to the greater margin of strength adopted for the specified conditions of working hydraulic head of pressure, is to the same extent stronger than a steel pipe when considered as a beam structure, as shown in the foregoing.

The collapsing pressures P (by formula (1A), page 56)

for cast iron and steel pipes of relative thicknesses usually adopted for the same internal working pressure of 150 lbs. per square inch are as follows, viz.:

Steel pipe 36 inch diameter, $\frac{3}{8}$ inch thick,
P = 51 lbs. per sq. inch.

Cast iron pipe 36 inch diameter, $1\frac{1}{4}$ inch thick,
P = 1025 lbs. per sq. inch.

The collapsing loads for a length of 12 feet represented by $P \times D \times L$, as in example, page 61, are as follows, viz.:

Cast iron pipe 36 inch diameter, $1\frac{1}{4}$ inch thick,
$= 1025 \times 36 \times 144 = 2371$ tons.

Steel pipe 36 inch diameter, $\frac{3}{8}$ inch thick,
$= 51 \times 36 \times 144 = 118$ tons.

Assuming that the steel pipe is capable of maintaining the circular form in resisting collapse, the maximum concentrated transverse breaking load W at the centre in tons would be as follows, from the foregoing formula, page 70, viz.:

$$W = \frac{3{\cdot}1416\, D^2 t S}{L} = 276 \text{ tons for cast iron pipe } 36'' \text{ diar.}$$
$$= 268 \quad ,, \quad \text{steel} \quad ,, \quad 36'' \text{ diar.}$$

It will thus be seen that the strength of the steel pipe when subjected to bending is limited to the load which produces collapse and that in this example it lacks the necessary stiffness to carry the ultimate transverse load of 268 tons and would therefore fail by collapse under the smaller distributed load of 51 lbs. per sq. inch = 118 tons as stated. On the other hand, it is shown that the cast iron pipe is capable of carrying a much greater distributed load tending to produce collapse than that corresponding

to the maximum transverse resistance of pipe section, so that the critical load for the cast iron pipe is that when considered as a beam structure under the conditions stated, viz., 276 tons at centre.

For a distributed load the relative theoretical strength of cast iron and steel pipe of the foregoing dimensions considered as a beam structure under the same conditions of external as that stated, apart from other considerations, is as follows, viz. :

Ratio of Critical Distributed Loads.

$$\frac{\text{Cast iron pipe, 36}'' \text{ diar. } 1\tfrac{1}{4}'' \text{ thick}}{\text{Steel pipe, 36}'' \text{ diar. } \tfrac{3}{8}'' \text{ thick}}$$

$$= \frac{\text{(Transverse) } 2 \times 276 \text{ tons}}{\text{(Collapsing) } \quad 118} = \frac{552}{118} = \frac{4{\cdot}66}{1{\cdot}00}.$$

Such an estimate is valuable in so far as it gives an idea of the relative theoretical limits of strength under conditions which may reasonably be assumed to occur incidentally in practice.

THE FLOW OF WATER IN PIPES AND OPEN CHANNELS.

For the supply of water, conveyance of sewage and other such work, the means employed may be either open channels or closed pipe conduits. The quantity of water conveyed is in all cases measured by the product of the cross sectional area of the stream, and the mean velocity of flow throughout that section.

In open channels the velocity of flow is dependent on the slope or fall in the surface of water throughout the length of the channel constructed to give the amount of fall in feet per mile required.

The relative values of the following factors, derived from extensive experimental data, were formulated by Eytelwein about the beginning of last century.

V = Mean velocity in feet per second.

Q = Quantity of water in cubic feet discharged per minute.

H = Fall or surface slope in feet per mile.

A = Sectional area of channel in square feet.

R = Hydraulic mean depth in feet

$$= \frac{\text{Sectional area}}{\text{Wetted perimeter or wall of channel}}.$$

$$S = \text{Sine of the angle of inclination} = \frac{H}{5280\,\text{feet (mile)}}.$$

Eytelwein's formula—

Mean velocity in feet per second

$$= V = \frac{10}{11}\sqrt{2RH}\,; \quad \ldots\ldots\ldots\ldots\ldots(1)$$

∴ Cubic feet per min.

$$Q = 60 \times \frac{10}{11}\sqrt{2RH} \times A = 54{\cdot}54\sqrt{2RH} \times A, \quad \ldots.(2)$$

Gallons per min.

$$6{\cdot}25 \times 54{\cdot}54\sqrt{2RH} \times A = 340{\cdot}87\sqrt{2RH} \times A.$$

The above formulae (1) (2) are applicable to oval, circular and other sectional forms of culvert, so long as they are not running full bore or under pressure like a closed pipe, which requires a modification in the coefficient as established by W. Prony in the following formula :

Mean velocity in feet per second

$$V = 48{\cdot}49\sqrt{D.S.}$$

$$= 48{\cdot}49\sqrt{\frac{D.H.}{5280}} = \frac{\sqrt{DH}}{1{\cdot}5}$$

Head in feet per mile

$$H = \frac{V^2 \times 1{\cdot}5^2}{D} = \frac{V^2 \times 2{\cdot}25}{D}$$

Example.

D = diameter of pipes in feet = 2 feet diar.
G = gallons discharged per minute = $Q \times 6{\cdot}235$.
H = fall of head in feet per mile = 26 feet.

$$Q = A \times \frac{\sqrt{DH}}{1{\cdot}5} \times 60 = 3{\cdot}1416 \times \frac{\sqrt{2 \times 26}}{1{\cdot}5} \times 60$$

$$= 907{\cdot}37 \text{ cub. feet per min.}$$

$$= 5657{\cdot}45 \text{ gallons} \quad ,,$$

In the older formulae the effect of friction due to variations in the nature of the wetted surface was not

sufficiently recognised, and it is the introduction of coefficients representing more accurately the roughness of wetted surface that distinguishes the later formulae from those of earlier date referred to.

The formula adopted by Taylor and Taylor in the construction of the valuable diagrams published by them is that of Herr Kutter, which has been frequently verified and further tested by them for cast iron pipe with the usual proportion of easy bends and undulations after being in the ground for some years. By adopting the coefficient of roughness N = ·013, they found the discharge of water from cast iron pipe to be quite in accordance with the results generally obtained in actual practice. For pipes newly laid with clean bright coated surfaces and uniform inclination, the coefficient N varying from ·0125 to ·012 might be used for greater accuracy according to circumstances.

In this formula the different factors are represented by the same letters with the addition of :

N = ·013 = Coefficients of roughness and other irregularities of the inside surface of pipe.

$$M = N\left(41{\cdot}6 + \frac{{\cdot}00281}{3}\right)$$

A = Area of pipe in square feet.

Herr Kutter's Formula.

$$Q = \text{cub. feet per second} = \frac{\sqrt{R}}{N}\frac{(M + 1{\cdot}811)}{(M+R)}A\sqrt{RS}.$$

Example.—A pipe 24 inches diameter with a fall of 26 feet per mile, say = 1 in 200 feet.

$$M = N\left(41{\cdot}6 - \frac{{\cdot}00281}{S}\right)$$

$$= {\cdot}013\,(41{\cdot}6 + {\cdot}00281 \times 200) = {\cdot}548\,;$$

$$\therefore Q = \frac{\sqrt{\cdot 5}}{\cdot 013} \times \frac{(\cdot 548 + 1\cdot 811)}{(\cdot 548 + \sqrt{\cdot 5})} \times 3\cdot 146 \times \frac{\sqrt{\cdot 5 \times 1}}{200}$$

$$= \frac{282\cdot 674}{17\cdot 759} = 15\cdot 9 \text{ cub. feet per second}$$

$$= 954\cdot 0 \quad ,, \quad ,, \quad \text{minute}$$

$$= 954 \times 6\cdot 235 \text{ gallons per minute}$$

$$= 5948 \quad ,, \quad ,, \quad ,,$$

The following formula has been adopted by some makers in estimating the quantity of water delivered by steel pipe :

D = Diameter of pipe in inches.
A = Area of pipe in square inches.
H = Head of water pressure in feet.
L = Length of pipe in feet.
M = Mean hydraulic radius in feet.
G = Gallons of water delivered per minute.

Constant = 260 for long lines of pipe with an average number of bends and fittings.

Constant = 300 for long straight lines of pipe.

V = Velocity of discharge in feet per second.

$$G = A \times 260 \times \sqrt{\frac{H}{L}} \times M.$$

Example.—A steel pipe 24 inches diameter with a fall of 26 feet per mile = a fall of 1 in 200 feet.

$$\therefore G = 452\cdot 39 \times 260 \times \sqrt{\frac{1}{200}} \times \cdot 5$$

$$= 5883 \text{ gallons per minute.}$$

And for a 24″ pipe diameter

$$V = \frac{G}{2\cdot 034 \times D^2} = 5\cdot 0271 \text{ feet per second.}$$

$$\therefore G = 5\cdot 0271 \times \frac{A}{144} \times 60 \times 6\cdot 235$$

$$= 5908 \text{ gallons per minute.}$$

Approximately the same as that just stated.

The following formula has also been extensively used to find the quantity of water discharged by long lengths of pipe :

H = Head of water pressure in feet.

Q = Quantity of water discharged in cub. feet per minute.

L = Length of pipe in feet.

D = Diameter of pipe in inches.

Constant = 22.

$$H = \frac{Q^2 \times L}{22 \times D^5}.$$

$$\therefore Q = \sqrt{\frac{H \times 22 \times D^5}{L}}.$$

Example.—A pipe 24 inches diameter with a fall of 26 feet per mile = 1 in 200 feet.

$$Q = \sqrt{\frac{1 \times 22 \times 24^5}{2000}}$$

$$= 935{\cdot}9 \text{ cubic feet per minute}$$

$$= 935{\cdot}9 \times 6{\cdot}235 = 5835 \text{ gallons per minute.}$$

The following is an abstract of the results obtained by each of the foregoing formulae, when applied to ascertain the quantity of water discharged by a pipe main 24 inches diameter under a head of water pressure 26 feet per mile, *i.e.* a fall of 1 in 200 feet.

(1) *By Prony's Formula.*

$$Q = A \times \frac{\sqrt{DH}}{1{\cdot}5} \times 60 \qquad = 907{\cdot}37 \text{ cub. feet per min.}$$

$$= 5657{\cdot}45 \text{ gallons} \quad ,,$$

(2) *By Herr Kutter's Formula.*

$$Q = \frac{\sqrt{R}}{N}\frac{(M - 1{\cdot}811)}{(M - \sqrt{R})} A \sqrt{R.S.} = 15{\cdot}9 \text{ cub. ft. per second.}$$

$$\therefore G = Q \times 6{\cdot}235 \times 60 \qquad = 5948 \text{ gallons per minute.}$$

(3) *By Steel Pipe Formula.*

$$G = A \times 260 \times \sqrt{\frac{H}{L}} \times M = 5889 \text{ gallons per minute.}$$

(4) *By General Formula.*

$$Q = \sqrt{\frac{H \times 22 \times D^5}{L}} = 935{\cdot}9 \text{ cub. ft. per minute.}$$

$$G = Q \times 6{\cdot}235 = 5835 \text{ gallons} \quad ,,$$

By the more recent formulae (2), (3) and (4) the estimated quantity of water discharged by a pipe 24 inches diameter under the same conditions of working head of pressure does not vary to any extent; it will be observed, however, that the discharge obtained by Kutter's formula (2) is greater by one per cent. than that from the steel pipe formula (3), although, as already stated, the results obtained by Kutter's formula (2) have been carefully verified by Taylor and Taylor and found to agree with the actual rate of flow of water through cast iron pipes even after they had been in use for some years. This suggests that the inside surfaces of cast iron pipe must have remained in a very perfect condition and unaffected by corrosion or other roughening influences. The small differences in the results obtained by each of the formulae (2), (3) and (4) may also be taken as evidence of the accuracy of the methods employed by the different authorities and the reliability of either formula in estimating the rate of flow and quantity of water discharged by a pipe under the fundamental conditions stated.

CONDITIONS AFFECTING THE FLOW OF WATER THROUGH PIPES.

In the foregoing considerations the quantity of water ascertained may be taken as the maximum obtainable when the pipe is new and free from obstructions, such as by differences in methods of construction which have the effect of reducing the clear area of the conduit, as compared with that of cast iron or steel tube with butt or lap welded joints.

When, however, a steel pipe is built up of plate sections with rivetted or other special form of jointing it becomes necessary to make allowance for the reduction of effective area, and in addition the increased friction caused by rivet heads or other projections, on the inside surface of such pipes. This is all the more important when the supply is maintained by means of an increase of pressure and corresponding increase in working cost of a power scheme, or, as in the case of a gravitation supply, with a limited head of pressure, where a reduction in the area of pipe is not so conveniently provided for to maintain the desired supply. The extent of increased resistance due to ordinary rivetted joints is sometimes estimated at 8 per cent.; when the different lengths of steel tube are tapered so that they may enter each other at the joints, the increased resistance may be estimated at 10 per cent.; in such cases the diameter of a rivetted steel pipe main

should be increased accordingly compared with that of the smooth bore cast iron or welded steel pipes with spigot and socket joints.

The following example bears evidence of the increased amount of frictional resistance to the flow of water through rivetted steel pipe. At Newark, N.J., a 48 inches diameter rivetted steel pipe was expected to deliver 50 million gallons per day, but delivered only 35 million gallons per day, *i.e.* 30 per cent. less than that estimated.

The discharge of water from different diameters of rivetted steel pipe compared to that delivered by means of cast iron or welded steel pipe of the same diameters with clean inside surfaces, has been estimated as follows :

The discharge of water by rivetted pipes—

4 to 11 inches diameter	= 30 per cent. less than that from cast iron and welded steel pipe without obstructions of any kind.
15 to 20 inches diameter	= 25 ,, ,, ,,
24 to 48 inches diameter	= 20 ,, ,, ,,

Herschel also obtained similar results from the East Jersey pipe main from which he estimated that the diameters for the same quantity of water delivered were as follows :

36 in. diar. cast iron pipe = 42 in. diar. rivetted steel pipe.
48 in. diar. cast iron pipe = 54 in. diar. rivetted steel pipe.

It is therefore evident that any reduction in the clear area of a pipe or an increase in frictional resistance due to structural differences are important factors when studying the initial cost of any installation with due regard to the true commercial value. For the same reason

it is necessary to take into account the quantity of water to be conveyed, also the relative properties of the proposed materials of construction to resist corrosive action, as experience has shown that owing to differences in quality of water and materials of construction, the rate of corrosive action varies to a considerable extent in different localities. With smaller sizes of pipe up to 8 inches diameter the growth of nodules of incrustation on the inside surface due to corrosion has developed in some instances to such an extent that the pipe has become completely choked. In pipes of larger diameters the same action merely reduces the effective area of the pipe. This growth develops at a rate diminishing as the thickness of covering increases, and when about 2 inches thick, it seems to protect the metal from further corrosive action. In such cases satisfactory results have been obtained by resorting to scraping where the margin of thickness, as in cast iron pipes, and other conditions permit, but this could not be recommended in the case of thin steel pipe, owing to the renewed active corrosion which takes place.

Apart from serious wasting of the metal and ultimate destruction of thin steel pipes by corrosion, it is important to consider here the effects of such growths inside in diminishing the quantity of water discharged by its reducing the clear area of the pipe and also by increasing the frictional resistance to the flow of water.

Perhaps the most important data on record regarding corrosion of pipes and its effect on the quantity of water discharged is that included in the various reports by leading experts appointed to investigate the cause and possible remedy for the excessive corrosion taking place in the 350 miles of steel conduit for the supply of 5,600,000 gallons of water in 24 hours to the Gold Fields in Western

Australia. The total cost of this work is stated at £3,260,000, of which the sum of £2,140,000 was expended on the pipe main.

The work of construction started early in 1898, and completed, so that water was delivered, in January, 1903, for the first time. (A period of five years.)

These steel pipes were of the following dimensions, with the "Lock Bar Type" of longitudinal jointing, viz.:

30 inch diameter $\frac{1}{4}''$ thick for a working pressure of 390 feet head.

30 inch diameter $\frac{5}{16}''$ thick for higher pressures than 390 feet head.

Tested under a hydraulic pressure of 920 feet head = 400 lbs. per sq. inch.

Tensile strength of steel plates specified to be from 25 to 29 tons per sq. inch.

Tensile strength of steel bars specified to be from 22 to 26 tons per sq. inch.

The necessary cutting, dovetailing and rolling of plates were carried out without heating either plates or bars. All pipes when completed and tested were afterwards heated to 300 degrees F. and coated by immersing in a mixture of coal tar and Trinidad asphaltum maintained at boiling temperture.

For the greater part this 30 inch diameter steel main has an earth covering about 2′ 3″ above the top of pipe. Where it crosses salt lakes it is carried on wood trestles and surrounded by an insulation of sawdust about 9 inches thick held on by galvanised iron wire.

The supply of water is maintained by means of pumping machinery arranged to form eight stations along the line of piping. During the first year, 1903, tests were made to ascertain the carrying capacity of the new main piping,

which showed that the frictional resistance, when delivering 5,600,000 gallons in 24 hours, was equal to 2·85 feet head per mile.

TABLE XX.

CARRYING CAPACITY IN 24 HOURS.

Section of Main.	Length of Section. Miles.	Originally provided for 2·85′ head per mile. Gallons.	At Sept. '08, with same head (2·85′ head) per mile. Gallons.	Reduction in Capacity per cent.	Equivalent diar. of New Pipe to carry present flow.
No. 2 Station to Point A. -	22·25	5,600,000	4,800,000	14	28·25
Point A. to Point B. - - -	12·00	,,	4,332,000	23	27·25
Point B. to No. 3 Station - -	42·25	,,	4,920,000	12	28·50
No. 3 Station to Point C. -	22·50	,,	4,560,000	19	27·75
Point C. to No. 4 Station - -	35·25	,,	4,632,000	17	28·00
No. 4 Station to Point D. -	6·50	,,	3,917,000	31	26·00
Point D. to No. 5 Station - -	20·00	,,	4,700,000	16	28·25
No. 5 Station to No. 6 Station	46·00	,,	4,870,000	13	28·50
No. 6 Station to No. 7 Station	31·75	,,	4,248,000	24	27·25
No. 7 Station to No. 8 Station	45·00	,,	3,348,000	40	25·00
No. 8 Station to point E.- -	12·25	,,	3,140,000	44	24·25
Point E. to Point F.- -	20·50	,,	2,640,000	53	22·50
Point F. to Point G. - -	23·50	,,	3,984,000	29	26·50

Table XX. shows the reduction in carrying capacity of each section since the service started in 1903 until September, 1908, a working period of five years.

In 1906 (three years from starting) attention was drawn to the possibility of internal corrosion, owing to the increase of pressure necessary at No. 7 Station to maintain the supply, it was therefore considered advisable to test the whole length of main pipe.

Note that the discharge of water in gallons per minute for a 30″ diar. steel pipe under a head of 2·85 feet per mile is obtained by the formula stated in page 76, viz.:

$$G = A \times 260 \times \sqrt{\frac{H}{L}} \times M$$

$$= 706{\cdot}8 \times 260 \times \sqrt{\frac{2{\cdot}85}{5280}} \times {\cdot}75$$

$$= 3205{\cdot}27 \text{ gallons per minute.}$$

$\therefore$ 3205·27 × 60 × 24 = 4,615,596 gallons in 24 hours.

The variation in the percentage reduction of capacity stated in Table XX., and shown graphically in diagram Fig. XII., suggested the idea that the rate of corrosion might have some connection with the length of time to which each section of the pipe was exposed to the heat and other atmospheric influence from the time it was coated until it was laid, jointed up and covered in the track; that, however, does not seem to have had any material effect, so far as can be ascertained by comparing the results of corrosion with the varying periods of exposure, and the different protective methods employed; the periods of exposure between the time of distribution to the laying of each section varied from 2·2 to 24 months.

The longer period corresponding to section point E to F.
The shorter ,, ,, ,, ,, A to B
referred to in Table XX.

The obstruction resulting from corrosive action as determined by the increased amount of friction due to the growth of tubercles on the various sections of the conduit

has so far shown no signs of diminishing, and if it should continue to develop at the present rate, the main it is said

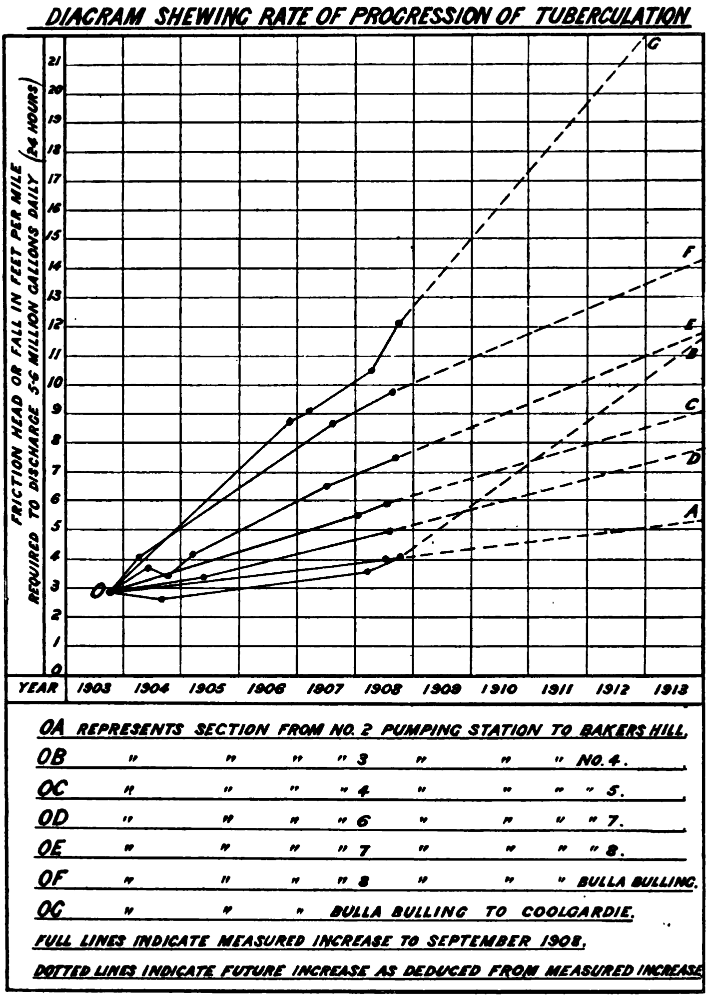


FIG. XII.

will soon be unable to supply the maximum monthly demand. It is anticipated, however, from other outside

experience regarding the progress of corrosive action in similar examples of steel pipes, that the rate of increase in resistance on that account may not continue to develop as assumed in the construction of the dotted extension lines shown in Fig. XII.

Full lines indicate the ascertained rate of increase in resistance due to incrustation up to September, 1908.

Dotted lines indicate the deduced increase for the future.

The gradual increase in the head of pressure required to overcome the increasing resistance in order to maintain the required supply of water through each section, is clearly shown on diagram Fig. XII.

The section of 30 inch diameter steel pipe which seems to have suffered least from corrosion is that between No. 2 Pumping Station and point A, Bakers Hill, a distance of 20¼ miles, as measured by the increase from 2·85 to 4 feet = 1·15 feet head per mile, the greatest resistance taking place in that section between points E and F from Bulla Bulling to Coolgardie, a distance of 20½ miles, in which the frictional resistance had increased from 2·85 feet when new up to 12 feet = 9·15 feet increase per mile, which shows an increase at the different sections throughout the main of 40·3 to 321·0 per cent. of the initial 2·85 feet working head per mile, and a corresponding increase in the cost of power, or on the other hand, with a constant head of pressure a corresponding reduction of from 14 to 53 per cent. in the quantity of water delivered, as stated in Table XX.

With pumping plant it is evident that the additional power required to maintain the head of pressure in excess of that in the original estimate for the specified quantity of water discharged, will be an actual loss, or otherwise a corresponding reduction in the available water supply.

CORROSION OF STEEL AND CAST IRON.

Most people are familiar with what is popularly known as rusting or corrosion of iron and steel, and if we enquire of tradesmen and others intimately acquainted with the behaviour of steel and cast iron as materials of construction exposed to the changing atmospheric conditions, we find where light steel has been adopted for fittings otherwise made of cast iron, that the opinion is altogether in favour of cast iron, as regard its lasting properties compared with the comparatively rapid destruction of similar steel structures by corrosion. Take, again, the small-bore steel tubes often used for branch service pipe connections to the usual cast-iron supply main ; experience has shown that these small steel tubes require to be specially treated in order to protect them from external corrosion and premature decay by having them embedded in asphalt, run into wood channels.

These and other familiar examples are important in so far as they confirm a very general opinion, which is at least suggestive of some fundamental property in favour of cast iron compared with that of mild steel to resist corrosive action when exposed under normal atmospheric conditions.

As indicating more precisely the relative merits of cast iron, wrought iron and mild steel to resist corrosive

action, H. R. Kemp in his *Rules and Tables* gives the following relative values :

Cast iron, rate of rusting represented by				100.
Wrought iron,	,,	,,	,,	129.
Steel	,,	,,	,,	133.

Questions of considerable scientific and commercial importance are nevertheless continually arising with regard to corrosive action generally and the relative merit of wrought iron, mild steel and cast iron ; the solution, however, is not always satisfactory owing to the complex nature of the subject with regard to variations in the chemical composition and physical properties of these metals, and the variety of conditions to which they may be exposed. Such investigations and research with regard to the relative corrosion of these important metals do not seem to have received the attention they deserve, with the result that present knowledge with regard to corrosion is more or less fragmentary and unsatisfactory for purposes of comparison.

Rusting of iron was at one time considered merely as a simple combination or chemical union of iron and ogygen to form iron oxide. While oxidation does take place when a piece of polished iron is heated to a temperature of 428° Fah. in a dry atmosphere, no direct simple oxidation is detected in dry air below that temperature ; any oxidation or rusting that takes place at normal temperature is due to the presence of moisture and free oxygen derived from the air, the destructive corrosive properties of which we have to consider.

By raising the temperature of the polished iron gradually from 428° to 600° Fah., it will be observed that the appearance of the surface changes from a pale yellow

through a rainbow-like series of colours, until at 600° Fah. the surface is a dark blue. These colours so familiar to tool smiths in the ordinary process of tempering are each due to the variations in thickness of the oxide of iron (Fe_3O_4) skin produced according to the degree of temperature to which the metal is raised. The thickness of oxide of iron so formed acts as a protective coating when the metal is exposed to the normal atmospheric conditions which otherwise would cause the formation of a highly porous form of oxide of iron, tending rather to stimulate corrosive action and ultimate destruction of the metal.

As indicating the complex nature of oxidation and destructive corrosion of iron, various theories have been suggested as an explanation of the chemical reactions taking place, including the simple oxide theory just referred to. The other theories which have been seriously considered are known as "THE ACID THEORY," "THE HYDROGEN PEROXIDE THEORY" and "THE ELECTROLYTIC THEORY." The more important of these are the ACID THEORY and ELECTROLYTIC THEORY.

By the Acid Theory held for many years, the destructive corrosive action or oxidation of iron is considered due to combined effects of water, oxygen and acid, a weak solution of carbonic acid being strong enough to change a portion of the iron into a very unstable ferrous salt ($FeCO_3$) with the evolution of hydrogen. The ferrous salt thus produced, is acted upon by the water and free oxygen forming hydrated ferric oxide ($Fe_2O_33H_2O$). The carbonic acid (CO_2) thus liberated is again free to attack another portion of the iron, so that the presence of a small amount of carbonic acid would continue the action indefinitely until the supply of water and oxgyen

gave out. Recent experiments, however, have shown that the presence of free acid is not essential to corrosion and that rusting of iron takes place when water and oxgyen are alone present.

The Hydrogen Peroxide Theory advanced by Traube in 1885 assumes the presence of iron, oxygen and water alone, and that the oxygen acts in two portions by which one portion combines with the iron to form unstable ferrous oxide (FeO). Various experiments have been carried out more recently to show that this theory cannot be reasonably maintained throughout.

The Electrolytic Theory now generally adopted was first advanced in 1903 by Whitney, who also suggested that corrosion of iron takes place independently of the presence of an acid, it having been established in his opinion that iron is soluble in pure water free from air, the iron being thus reduced by passing into solution in the ionic form. Water is said to contain a small proportion of ionized molecules yielding hydrogen (H) and hydroxylions (HO) of opposite polarity. The metallic iron passing into solution as ferrous salt (FeO) is accompanied by a transfer of electro-positive hydrogen ions which are thus converted into atoms of free hydrogen gas on the surface of the iron. The solution of ferrous salt ($Fe(OH)_2$) formed when exposed to the action of free air in solution is rapidly oxidised further to the ferric condition as red hydrated ferric oxide ($Fe_2(OH)_6$) which is now precipitated in the form of rust.

* The ferrous salt ($Fe(OH)_2$) is formed thus :

$$Fe + 2H_2O = Fe(OH)_2 + H_2,$$

and the hydrated ferric oxide $Fe_2(OH)_6$ is formed thus :

$$2Fe(OH)_2 + O + H_2O = Fe_2(OH)_6.$$

* Chemical equation suggested by Newton Friend.

It will be seen, therefore, that the formation of rust is started without the presence of free oxygen or carbonic acid, an electrical current being set up due to difference in potential between the iron ions passing outward into solution and the hydrogen ions from the electrolytic pure water towards the iron, the process being continued indefinitely.

Electro-chemical action and its resultant corrosion of iron and steel structures may also be explained as due to consequent electrical currents set up between the iron and dissimilar connected substances of which the metal of the pipe is composed, when these are exposed to moisture or other electrolyte such as dilute acid solutions, with which the soil surrounding the pipe may be saturated.

The corrosive action thus set up by consequent polarity corresponds to that which takes place in the simple elementary zinc-copper sulphuric acid cell of a galvanic battery, in which the electric current set up is due to the liquid contact of two dissimilar metals, copper and zinc, within the cell, and metallic contact outside by wire or other suitable conductor, as shown at A and B, Fig. XIII. The same action taking place as shown at C when the metallic contact is within the acid solution, as for example, the local galvanic action between dissimilar metallic or other particles at the surface of the pipe and in contact with an electrolyte.

The strength of electric current thus set up depends on the difference of potential between the two materials taking part in the reaction and the resistance of the circuit. The direction of current through the liquid solution is from the electro-positive metal to the electro-negative, the former of which always goes into solution while the latter is unaffected. In the example referred

to, the zinc being electro-positive to copper, the zinc therefore becomes dissolved and passes into solution

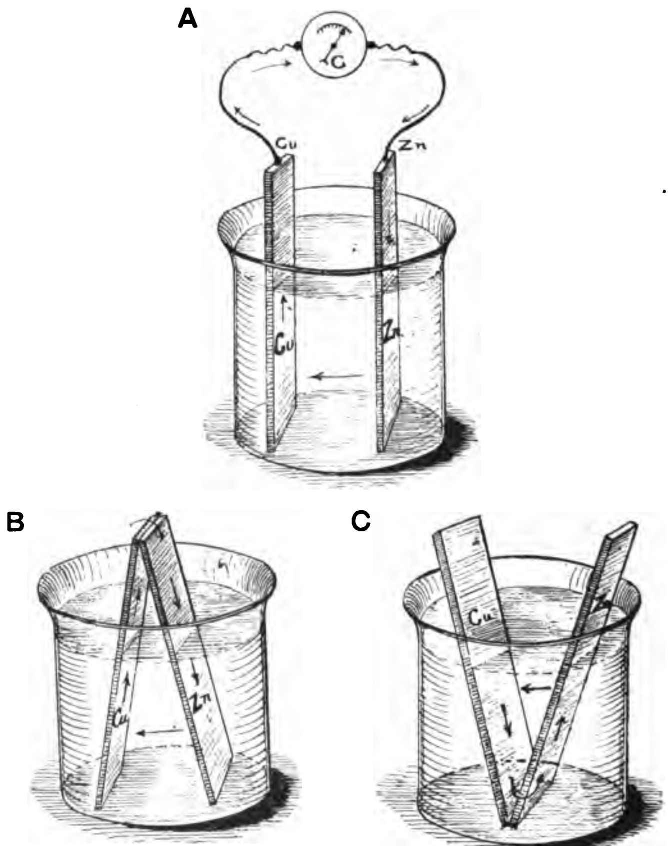


FIG. XIII.

as zinc sulphate ($ZnSO_4$), while the copper remains unaffected.

Some idea of the relative intensities of electromotive force and corresponding strength of current obtained by adopting different pairs of metals under the foregoing

electro-chemical conditions, illustrated in Fig. XIII., is derived from the results obtained by Volta in his researches regarding the differences of potential produced by contact of different pairs of metals, as shown in the following series.

Contact Series of Metals.

	Name.	Difference of Potential. (Ayrton and Perry.)
Electro-positive.	Sodium - - -	
	Manganese - - -	
	Zinc - -	=·210 Volts.
	Lead - -	=·069 ,,
	Tin - -	=·313 ,,
	Iron - -	
	Hydrogen -	=·146 ,,
	Copper -	
	Silver -	
	Gold - -	=·238 ,,
	Platinum -	=·113 ,,
	Graphite carbon	
Electro-negative.	Oxygen - - -	
		1·089

[In this series, reading from the top, each metal is electro-positive to the metal immediately below, the actual values stated for these differences of potential being measured later by Ayrton and Perry.*] From Volta's Law the difference in potential between any two metals of the series is equal to the sum of the differences of potential between the different pairs of metal that lie between them in the contact series. So that the total difference of potential between zinc and graphite is equal to 1·089 volts.

As already stated, when two metals are placed in a suitable liquid solution and electrically connected, as indicated at A, B and C, Fig. XIII., the electric circuit is completed, and the current passes from the copper to the zinc through

* See Silvanus P. Thomson's *Electricity and Magnetism*, p. 69, 1882.

the wire outside, as at A or where the metals are in direct contact, as at B and C, from the electro-positive zinc through the liquid medium to the electro-negative copper; thus it is the relatively positive in any pair of metals in the series that goes into solution, while the other relatively negative metal remains unaltered. If a piece of iron is made to take the place of the copper, the zinc being still relatively positive to the iron, the direction of current will be the same and the zinc is again dissolved, while the iron is unaffected. If now pieces of iron and copper are placed in the cell as at A, Fig. XIII., the iron as shown in the series will now be electro-positive to copper. The electric current set up will therefore flow from the iron to the copper through the liquid solution, and the iron will thus dissolve and waste away.

The current in any circuit depends on the difference of potential or electro-motive force and the resistance of the circuit as represented by $C \text{ (amperes)} = \frac{E \text{ (volts)}}{R \text{ (ohms)}}$. Therefore the rate of electro-chemical action will be in proportion to the current and the difference of potential. The rate at which corrosion of the metal proceeds will be greatest when the metals are those relatively furthest apart in the series. It should be pointed out, however, that the order and potential difference of these metals is not the same for any electrolytic solution, and it has been stated that, in some instances, the same two metals when placed in certain electrolytic solutions produce an electric current in the opposite direction from that with other solutions, and the metal which in the one electrolyte was unaffected becomes electro-positive and goes into solution with the other electrolyte. The fact that such variations even to the extent of a reversal of electro-

chemical action are said to occur, shows the importance of extended knowledge and the necessity for careful observation of all the circumstances affecting corrosive action before the relative merits of any two metals can be ascertained with due regard to the nature of conditions in each case.

In the foregoing examples rapid electro-chemical action is shown to take place when two dissimilar metals are placed in a simple cell containing an electrolytic solution or dilute acid and are in direct contact outside or otherwise connected as by means of a wire in order to complete the electric circuit. When outside contact is broken and the two metals have become electrically isolated, rapid corrosive action ceases. A certain amount, however, of those metals continues to dissolve and pass into the liquid solution at a rate depending on the purity of the metal; as such impurities are usually electro-negative and set up local galvanic action throughout the surface, and when iron is relatively electro-positive, iron is the metal which continues to corrode. This is clearly demonstrated with samples of iron and steel, the purity of which was represented by the percentage of iron each contained, and when, as in the case of the ingot steel referred to in page 7, the iron contained is as high as 99·92 per cent., local galvanic action and its corresponding corrosive effects are so reduced, that it becomes of no account practically. If then pure iron could be used for constructional purposes, it would seem to be capable of resisting corrosion due to local galvanic action. It is just this difficulty in producing a suitable quality of iron or steel of sufficient homogeneity and purity throughout that constitutes to a great extent the difficulties to be overcome in dealing with excessive corrosion of iron and steel structures generally.

Mild steel, as has been shown in the foregoing Tables, contains quite a number of substances which vary in amount and relative proportions according to the physical properties of the metal required. When the metal leaves the steel furnace and has just been poured into the ingot mould, these so-called impurities are diffused uniformly throughout the liquid mass. As the metal cools down and is becoming solid, a certain amount of segregation takes place owing to the differences in the temperature at which the respective metallic and metalloid compounds solidify. When the steel ingot is subsequently rolled out, these differences in composition have a marked influence in producing corresponding variations throughout a certain definite area of the finished plates, the more impure portions being generally electro-negative to the purer metal, so that in the event of such surfaces being exposed to an electrolyte, galvanic action will be set up, with the result that the anodic iron is the part affected by corrosive action referred to. During the rolling process, the highly heated metal also develops other irregularities throughout the surface, due to the formation of a coating of oxide of iron, which forms a skin of oxide ($Fe_3O_4 + Fe_2O_3$) known as mill scale. This adheres firmly in patches over the surface of the metal. Before painting the surfaces of steel structures it is important to have this scale removed by chipping or other means. If allowed to remain adhering to the surface in the case of underground steel pipe in contact with soil containing weak acid or other electrolytic solution, the mill scale being electro-negative to the mild steel plate, it is, therefore, the metal forming the shell proper that suffers by corrosion more or less throughout the surface due to this local electro-chemical action.

The following is an example of corrosion and its effects on mild steel plates from a detailed report by E. Kuichling regarding the condition of the conduit for the Rochester Water Works, America, U.S.A., constructed in 1893-4. This conduit consists of a 38-inch diameter rivetted steel pipe, 26 miles long, ranging in thickness from ¼″ to ⅜″. Three different kinds of protective coating were applied at different sections, viz.:

First: Californian asphalt.

Second: a mixture of refined Trinidad and coal tar pitch.

Third: a baked or japanned coating proposed by Prof. A. H. Sabin.

In spite of the greatest care throughout the construction, serious corrosion of the metal began to appear in 1901 (seven years after completion) in the first and second sections. The examination was continued throughout the entire route by excavation, which showed that the steel pipe was more or less pitted.

Up to the end of 1907, a total of 205 perforations of the steel by corrosion were found and repaired, all of which but one occurred in the ¼-inch thick plates.

The plates of the main were supplied by the Pennsylvania Steel Company, and protected by the Sabin method of japanning. The remainder, a little more than one-half of the plates, were made by the Carnegie Steel Company and protected with Californian and Trinidad asphaltic coating. Both metals were prepared by the open-hearth process from the same specification, which limited the composition to the following percentages:

Sulphur - - - - -	·06 per cent.
Phosphorus - - - -	·06 ,,
Manganese - - - -	·60 ,,

Physical Properties.

Ultimate tensile strength from 55,000 to 65,000 pounds per sq. in., *i.e.* from 24·5 to 29 tons per sq. in.

Elastic tensile strength, 30,000 pounds = 13·4 tons per sq. inch.

Elongation, 22·5 per cent. in a length of 8 inches.

Cold bending, punching, drifting and forging tests.

Out of the total 205 perforations only 16 occurred in the plates made by the Pennsylvania Steel Company, which contained a considerably smaller percentage of manganese than that contained in the product of the Carnegie Steel Company (the effect of manganese on corrosion of steel is referred to in pages 13 and 14 ; and the composition of ingot steel, page 7). The steel plates made by the Pennsylvania Steel Company exhibited a much greater resistance to rusting than the others made by the Carnegie Steel Company.

The soil was mostly blue clay, and the ground water comparatively free from corrosive acids or gases, so that Prof. F. L. Kortright, after a careful study of the problem, ascribed the cause of rusting as mainly due to the action of Mill Scale, Oxygen and free Carbonic Acid, at points where the coating was defective.

E. Kuichling also referred to a similar experience he had with corrosion and pitting of the rivetted steel conduit that supplies drinking water to the city of Portland, Ore. This conduit consists of a 42-inch to 33-inch rivetted steel pipe, 24 miles long, from $\frac{3}{8}''$ (·375) to $\frac{1}{5}$ (·20) inch thick, and the distributing pipes from 30 to 18 inch diameter rivetted steel from $\frac{1}{4}$ (·25) to $\frac{1}{6}$ ($1\dot{6}\dot{6}$) inch thick.

These pipes were made from eastern steel plates under the same general specifications that were used for the

Rochester conduit, and were coated with Californian asphalt or maltha. Mr. D. D. Clarkes, the engineer of the Portland Water Board, stated that the severest corrosion occurred where the pipe was laid in clay, and that little injury from rust was observed in sandy and gravelly ground. Comparing the foregoing experience of mild steel pipe with that of the 36 and 24 inch diameter rivetted WROUGHT IRON pipe ranging from $\frac{1}{4}$ inch to a little more than $\frac{1}{8}$ inch thick, which did comparatively good service in the original water works of the City of Rochester, N.Y., also with that of other examples where wrought iron plates were used. The evidence as to the relative merits of mild steel and wrought iron to resist corrosion is in favour of wrought iron. With the introduction of steel in the construction of ships, it was also soon observed that the corrosive action of steel plates, etc., was a much more serious matter than formerly experienced, when the constructional material was wrought iron throughout.

OTHER INFLUENCES AFFECTING CORROSION.

Corrosion of mild steel is found to develop at a comparatively early stage, particularly where the metal has been bent into special forms, hammered caulked, or otherwise treated cold in the production of mild steel

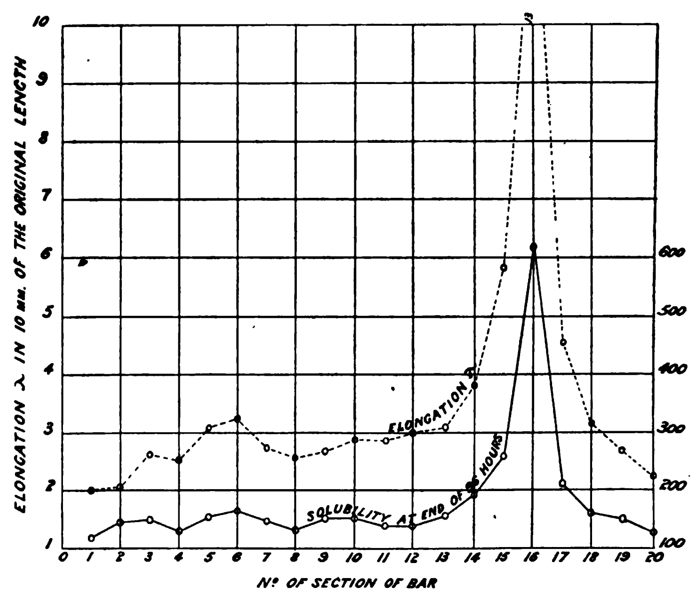


FIG. XIV.

structures. Corrosive effects are, therefore, often first observed round rivet heads and along the edges of plates, where the metal has been subjected to caulking. Annealing will to some extent restore the original properties of the metal in this respect.

In order to examine more fully the corrosive effects of cold working and varying stresses thus produced, Heyn and Bauer proceeded to investigate the corrosive effects on pieces of steel previously subjected under tension up to the breaking load. By this means they obtained a series of small test pieces each of which represented a definite amount of stress and stretching according to its original position in the test bar relative to the point of fracture where the maximum amount of stretching takes place.

In these researches of Heyn and Bauer the relative corrosive effects were ascertained by testing the solubility of the different test pieces in dilute sulphuric acid. The composition of the steel in these tests is as follows, viz.:

Carbon - - - - -	·07	per cent.
Silicon - - - -	·06	,,
Manganese - - - -	·10	,,
Phosphorus - - - -	·01	,,
Sulphur - - - -	·019	,,
Copper - - - -	·015	,,

The test bar previous to its being subjected to tensile stress, was marked off as indicated in Fig. XV. into twenty equal parts, 1 c.m. in length, each of which was again carefully measured after the test bar had been stretched up to the breaking point; from each individual part cut off, small test pieces 0·9 c.m. diameter and 1·0 c.m. in length, were turned down so that the axis coincided with that of the original test bar.

These small test pieces were now subjected to the corrosive action of one per cent. sulphuric acid, and the loss in weight of each determined after such treatment for ninety-six hours. The results obtained are shown in

Fig. XIV. It will there be seen that the full line curve for solubility closely follows the dotted curve representing the relative amounts of elongation, thus confirming the deteriorating effect of initial stresses and strains produced in the working of mild steel.

The effect of stretching, bending, twisting and hammering on the corrosive properties of steel has been tested by various other authorities by subjecting sections of strained and unstrained portions of steel cut from test pieces subjected to the mechanical treatment referred to.

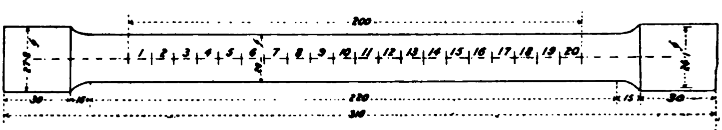


FIG. XV.

Both the strained and unstrained sections being now placed in a cell, where they were sufficiently submerged as before in a suitable dilute acid solution, and connected by a wire and galvanometer in circuit, as shown at A Fig. XIII., page 92, so as to ascertain the strength and direction of electric current set up between two pieces of the same steel, differing only as regards the amount of stretching or other mechanical distortion to which the test pieces were subjected. The results obtained were in some cases rather conflicting, but in all cases galvanic action took place, indicating that differences of potential are set up where the metal is subjected to irregular straining by cold working in the process of manufacture, and that this may account in some cases for local galvanic action and the resulting corrosion and pitting of steel structures.

Annealing the steel after such mechanical treatment will largely reduce the tendency to corrosive action.

A series of experiments was carried out on these lines as suggested by Professor Alwin Nachtweh, Hanover, and Prof. Kurt Arndt (Dr. Phil.), Charlottenburg, about five years ago. There sults obtained are shown in diagram,

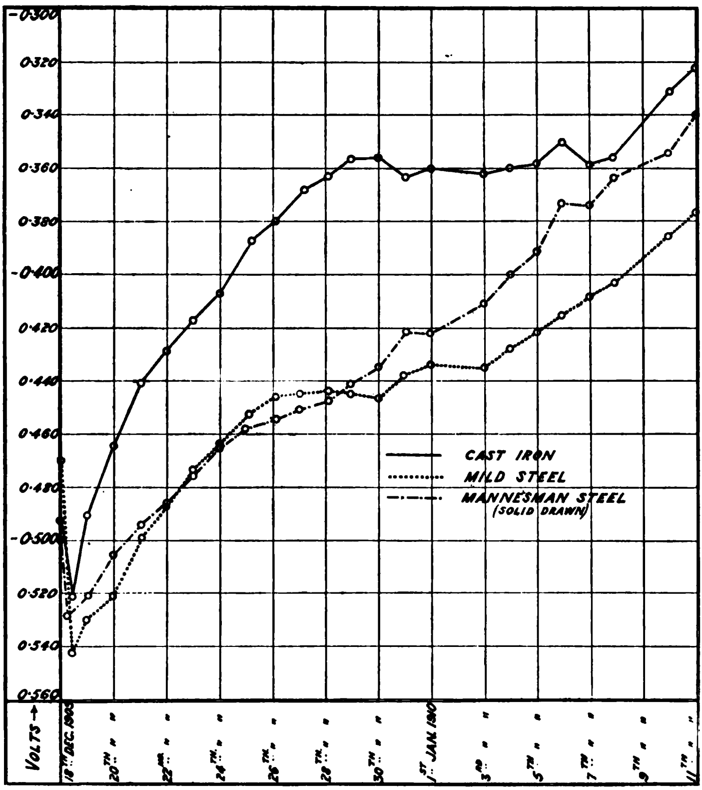


FIG. XVI.

Fig. XVI., the horizontal measurements representing the period of time, and the vertical ordinates the corresponding differences of potential set up.

In Fig. XVII., page 104, these results are shown to a larger scale, relative to the zero or datum line representing

cast iron, so that the curves for mild steel and Mannesman steel show the differences of potential and corrosive effects compared to cast iron under the same conditions.

It will be seen from these diagrams for potential differences recorded between a constant electrode (mercury) and the electrodes of cast iron, wrought iron and

Fig. XVII.

mild steel varied, that the difference was least in the case of cast iron and greatest when steel was used as the other electrode. The increased difference of potential and corresponding electro-chemical corrosive action, thus set up with steel, as contrasted with that for cast iron, gives evidence of the superiority of cast iron to resist corrosion under the conditions stated.

Fig. XVIII., page 105, was constructed by the same authorities from data obtained by them regarding the relative corrosive properties of cast iron, wrought iron and mild steel, as indicated by the quantity of oxygen absorbed by each of these three metals, exposed in moist air.

Test pieces 6 c.m. diameter outside and 20 c.m. long approx. ($2\frac{1}{2} \times 8$ inches long) were cut from pipes of cast iron, wrought iron and mild steel, and each placed in a separate glass cylinder, 30 c.m. high approx. (12 inches), into which a little water was poured ; the bottom edges of these test pieces were kept out of contact with the water by resting on pieces of paraffin wax. The glass cylinders were then

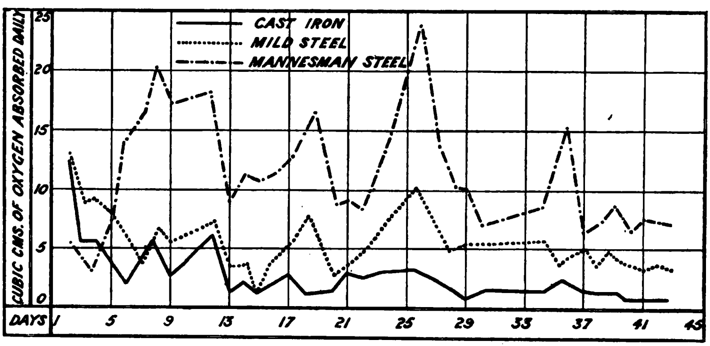


FIG. XVIII.

closed air-tight by a rubber stopper, through which a glass tube was inserted in order to connect the interior with one of Hempel's gas pipettes, by this means it was possible to observe exactly the amount of oxygen absorbed each day from the reduction in the volume taking place in each cylinder. The necessary corrections for temperature and atmospheric pressure were made in order that the volume in cubic c.m. might represent as accurately as

possible the relative merits of the three metals to resist corrosion when thus exposed to the action of slightly moist air.

The results shown graphically in diagram Fig. XVIII., are also stated in the following Table No. XXI. :

TABLE XXI.

Time in Days.	Cubic Centimetres absorbed by:		
	Cast Iron.	Mild Steel.	Mannesman Weldless Tube.
1	13	13	5
3	24	32	8
5	30	45	30
10	45	63	109
20	59	108	198
30	73	156	293
43	95	213	389

By comparing the three curves it will be noticed that at first the cast iron obsorbed oxygen more rapidly. In a few days, however, the rate of absorption for cast iron had considerably diminished, while on the other hand the absorption of oxygen by wrought iron and mild steel had considerably increased out of all proportion. Here again the results show the superiority of cast iron to resist corrosion when compared with mild steel.

TESTING BY EMBEDDING IN MOIST SAND.

Test pieces cut from pipes of the different materials shown in the following Fig. XIX. were embedded in fine sand, viz.:

No. 1. Cast iron.

No. 2. Dusseldorf soft fusing iron (mild soft steel).

No. 3. Lauchhaum steam pipe (mild steel).

No. 4. Mannesmann hard fusing iron (hard steel).

These were allowed to remain buried for a period of eight weeks, during which the sand was moistened three times, so that the moisture amounted to an average of three to four per cent. When examined at the end of the test period stated, the quantity of rust formed on each piece of pipe gave evidence of the superiority of cast iron as in the previous tests.

In order to ascertain whether or not the superior rust-resisting properties of cast iron observed could be attributed to the hard skin formed at the outer surface of cast iron, as already suggested, each piece of pipe was prepared by removing a portion of the skin 2 c.m. $\times$ 2·5 c.m. (·787 $\times$ ·984 inches), and smoothing the surface with a file, the remaining surface being coated with tar compound. The different pieces of pipe were now embedded in moist rough sand for a period of three weeks; it was then observed that the polished surface of cast iron was unaffected except that it had developed a slight greenish discolouration, while

the other three pieces of steel were more or less covered with a coating of rust which had cemented grains of sand to the polished surfaces. The pieces of pipe were again embedded for another week (a total period of four weeks), when they were finally taken out. The corrosive effects on the polished surfaces of these metals are clearly indicated in Fig. XIX., obtained from photographs taken of each piece of pipe, the disturbing glare by reflection from the adjacent coated surface being avoided by covering the coating with black paper, leaving an aperture as shown. It is here evident that the polished surface of cast iron was unaffected excepting the slight discolouration which had now become yellow, whereas the surfaces of the three pieces of steel similarly treated showed that corrosive action had already developed to a considerable extent.

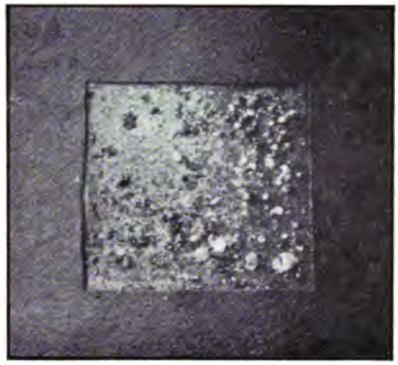
J. N. Friend, Ph.D., D.Sc. (Birmingham), in his recent treatise on the corrosion of iron and steel, states that to resist corrosion cast iron in many ways is superior to wrought iron or steel, especially when it is close grained, and he also gives the following table, No. XXII., showing the results obtained by Thwaite in 1880 after collecting together all such available information, and from these, it appears, he considers that the outer skin formed during the casting acts as a preservative coating much in the same way as iron and steel are protected by a film of oxide produced by the Bower-Barff process.

The results obtained throughout these tests, it will be seen, have all gone to prove the superiority of cast iron to resist corrosion as compared with wrought iron and steel, and quite confirm reports from all quarters regarding the excessive corrosion of steel structures generally and underground pipe in particular; on the other hand, underground cast-iron pipes, as regards corrosion, have

No. 1.

Cast Iron.

No. 2.



Mild Soft Steel.

No. 3.

Mild Steel.

No. 4.

Hard Steel
(Mannesman fusing iron).

Fig. XIX.

Facing p. 108.

successfully stood the severe test of time under various conditions.

TABLE XXII.

RELATIVE CORROSION OF WROUGHT IRON AND CAST IRON.

Metal.	Foul Sea Water.	Clear Sea Water.	Foul River Water.	Pure Air and Clear River Water.	City Air or Sea Air.
Wrought Iron	10·450	5·855	7·680	0·655	6·690
Cast iron	3·500	3·386	2·034	0·604	2·637
Cast iron (skin removed by planing)	12·275	4·738	3·884	0·584	4·763

Corrosion and its influence in determining the useful life of cast iron and steel pipe is therefore a subject of the highest importance to engineers and others responsible for the success or failure of undertakings involving the use of pipe.

The rate at which corrosive action proceeds has been shown to be dependent on the electro-chemical action set up, due to difference of potential between the electro-positive iron and its electro-negative impurities, when these are in contact with an electrolytic solution. The rate of corrosion with the same metal will thus depend on the nature and strength of the acid solution which varies to considerable extent in different localities. Water usually contains free oxygen and carbonic acid. When, however, moisture or water are restricted sufficiently, the rate of rust formation is comparatively slow. This is in accordance with the results of experiments carried out by Edward S. Simpson, B.E., F.C.S., Government Mineralogist, Perth, Western Australia, who also found that the rate of corrosive action and amount of rust formed is

nearly doubled by the presence of a little common salt (sodium carbonate), or a mixture of magnesium chloride and sodium nitrate, whilst it is considerably increased in the presence of a little calcium carbonate, chloride or sulphate of magnesia, sodium sulphate or nitrate.

The relative amount of corrosion or iron oxide formed and deposited in a water solution of the following soluble salts representative of the various electrolytes which occur in soils is indicated in the following :

Rust slowly	Water or Moisture with Free oxygen from dissolved air and Carbonic acid.

In these tests the following percentages were adopted :

		Per cent. solution.
Rate of Rusting doubled in the presence of a little	Sodium chloride (common salt)	1
	Sodium carbonate (washing soda)	1
	Magnesium chloride and	½
	Sodium nitrate mixed	½
Rate of Rusting considerably increased in the presence of a little	Calcium carbonate (lime)	1
	Calcium chloride	—
	Magnesium sulphate	—
	Sodium sulphate	1
	Sodium nitrate	1

The intensity of corrosive action at different points of the 30-inch diameter steel main for the water supply to the Goldfields in Western Australia already referred to, was found to confirm the foregoing conclusions, the rate being greater as the total amount of salts is increased, and still more whether or not those salts are derived from acids which have a strong affinity for iron, and also that chlorides, sulphates and nitrates may be expected to have the most injurious effect as stated.

INTERNAL CORROSION.

In the case of internal corrosion, the presence of salts and other impurities in the water conveyed is limited in order that it may not only be potable but free from the presence of impurities in sufficient quantities as to be injurious to health. Nevertheless such impurities exist to a greater or less extent in all water supplies, with the result that in certain localities the corrosive action of the water destroys the pipe through which it is conveyed within a comparatively short time.

Internal corrosive action is more insidious than when it is exposed surfaces that are attacked. Not only does it cause the destruction of the metal forming the pipe, but the resultant growth of incrustation causes a reduction in the clear area of the conduit, frictional resistance to the flow of water is also increased, with the result that the carrying capacity of the pipe in some cases is seriously affected, as already pointed out. When internal and external corrosion are going on at the same time the life of the pipe will be correspondingly reduced. In some cases, the pipe is laid above ground or in an exposed position, which permits of the external surface being frequently examined and recoated when necessary with paint or other protective material, so that the external surface may be maintained in perfect condition while unsuspected corrosion is going on inside. A striking

example of this is the 12-inch diameter welded steel pipe laid across the New Tay Bridge at Dundee, no doubt adopted for some good reason at the time. The pipe in such a position was easily accessible and convenient for external examination and painting, and therefore maintained apparently in perfect condition throughout, until something occurred which led to the exposure of the interior of the pipe now in service for some years. It was only then discovered that corrosion was going on at a very rapid rate and had already developed to such an extent that it was considered necessary to make arrangements for its replacement. Here we have a cast-iron pipe unaffected by corrosion, and a mild steel pipe seriously affected by corrosion when conveying the same quality of water, under exactly the same conditions. This instance constitutes a thoroughly practical example from which to draw conclusions, and must, therefore, be considered as important evidence of the superiority of cast iron pipes to resist corrosive action as compared with mild steel pipes under the same condition as regards quality of water conveyed, etc.

The 30-inch diameter steel main to Coolgardie affords another example of serious internal corrosion of steel pipe, which, it is said, if not checked by some means, may lead to the ultimate failure of the supply apart from the additional deteriorating effects taking place on the outside surface due to external corrosion.

When external and internal corrosion goes on simultaneously it may not take long to develop serious pitting and even perforations in a pipe initially thin, with corresponding leakage and loss of water, apart from the loss of strength, reduction of effective area, and increased resistance to the flow of water. As indicating the serious

effects of such leakage, particularly when the water is conveyed through very long mains, it has been pointed out that small leakages to the extent of 5 per cent. on a 20-mile section amount to nearly 90 per cent. of the total quantity of water conveyed through a main 350 miles long. In the following analysis, from the joint report of Deacon, Ramsay & Hehner, 1909, it will be seen that the Kalgoorlie water contains a considerable proportion of sodium chloride, magnesium chloride, also minute quantities of carbonates and free carbonic acid, the presence of which would account for a more than usual amount of corrosion. Comparing the effect of samples of this water with London water, containing 8·9 parts of combined carbonic acid, they found that the relative activity of these two waters running slowly over the steel plate for a week, was as follows :

	Rate of corrosion per week.
With Goldfield Water	= 2·38 milligrammes per sq. cm.
	= ·004874 lbs. per sq. foot.
With London Water	= 1·72 milligrammes per sq. cm.
	= ·003522 lbs. per sq. foot.

COMPOSITION OF KALGOORLIE WATER.

Mt. Charlotte Service Reservoir.

Sodium Chloride	25·49	parts in 1000·000.
Magnesium Chloride	5·46	,, ,,
Calcium sulphate	2·17	,, ,,
Calcium carbonate	·78	,, ,,
Magnesium carbonate	·99	,, ,,
Silica	·38	,, ,,
Iron oxide	·02	,, ,,
Mineral solids	35·29	,, ,,
Free carbonic acid (CO_2)	·68	,, ,,
Combined ,, ,,	1·29	,, ,,

The growth of incrustation as the result of corrosive action on the inside surface of iron and steel pipes, by its appearance gives rise to the popular impression that it is due to earthy matter mechanically suspended in the water conveyed and subsequently deposited throughout the inside surface of the pipe. If this were the case, analysis of such incrustation would show a correspondingly high proportion of silica and alumina, as these are the chief constituents of earthy matter generally. This idea, however, is not supported by E. A. Maine's analysis of the nodules forming internal incrustation, the composition of which he gives as follows :

COMPOSITION OF INTERNAL INCRUSTATION.

Moisture	H_2O	= 4·12	per cent
Water of hydration	H_2O	=11·34	,,
Silica	SiO_2	= 2·20	,,
Sulphur	S	= ·76	,,
Carbon	C	= 1·05	,,
Ferric oxide	Fe_2O_3	=73·53	,,
Magnetic oxide	$Fe_3O_4+Fe_2O_3$	= 6·54	,,
Alumina	Al_2O_3	= ·39	,,
Manganese	Mn_3O_4	=Trace	
		99·93	

The absence of earthy matter in this instance indicates that the growth of internal incrustation in general is essentially due to the corrosive action of the water flowing through the pipe on the metal of which the pipe is constructed, the electro-positive iron being dissolved, and subsequently oxidised by oxygen from the air in solution to form hydrated oxide, which accumulates as rust in the form of numerous nodules or tubercles, each of which has a characteristic structure and conical limpet-like shape, the face directly opposed to the flow of water

being generally less inclined than that looking down stream.

The area at the base of these nodules corresponds to a certain amount of local corrosive action and pitting, which in a steel pipe extends to about $\frac{1}{8}$ of an inch in depth at the centre and diminishes towards the outside; the surface thus affected continues to increase so that the corrosive effects produced by the adjacent nodules extend into each other, and may thus cover large areas, even to the extent of the entire surface of the pipe. These nodules, it has been shown, consist chiefly of iron dissolved out from the pipe, forming a soft mass with a characteristic black core at the centre, becoming yellowish outwards to a reddish brown at the outer surfaces.

Internal corrosive action has been found by experience to diminish with the growth of these nodules, due to the resistance of the deposit increasing as the process develops, until a point is reached when the incrustation becomes a sufficient protection to retard further corrosive action of a serious nature compared to that when the metal surface was clean. Opinions have, therefore, differed with regard to the merits of the use of scrapers for the removal of internal incrustations in order to increase the quantity of water delivered for a time, the cleaned surface by this means being exposed to renewed active corrosion which previous to scraping had almost ceased.

In this respect the greater initial thickness of cast iron pipes is more favourable to the use of scrapers compared with steel pipes, as the greater thickness permits the removal of a certain amount of metal without any material reduction in the margin of strength. It might, however, be dangerous to similarly treat a thin steel pipe suffering

to the same extent, more particularly if the outer surface is also suffering by corrosion and pitting.

The absence of unfavourable reports regarding cast-iron pipes during these many years compared to the numerous records of failure more recently with steel pipes, is no doubt due in a measure to the extra thickness of cast-iron pipes, apart from the general superiority of cast iron to resist corrosion.

When the surface of a cast-iron pipe is exposed to electrolytic action and a portion of the iron becomes dissolved to form nodules of rust, a black solid substance composed of iron, iron oxide, carbon and silica is formed, which takes the place of the metal without any apparent change in the thickness or surface of the metal. In the event of scrapers being used, this substance is sufficiently hard and cohesive to act as a buffer, and thus protects the metal from the renewed attacks of corrosion referred to.

In his report regarding the Coolgardie Pipe, E. A. Main, Government Analyst, gives the following analysis of this black substance taken from the inside surface of a cast-iron pipe in a powdered state by means of a sharp chisel.

	A.	B.
Water - - - - -	13·42	13·42
Silica or Silicon - - -	4·98 (Silicon)	10·68 (Silica)
Iron (metallic) - - -	19·30	19·30
Ferrous or ferric oxide -	52·42 (Ferric)	47·19 (Ferrous)
Carbon - - - - -	9·48	9·48
Sulphur - - - - -	·46	·46

This powder, he also states, when exposed to the air, became so hot that the moisture it contained was driven off in the form of steam, and in the solid form before removal it could be cut or scraped with a knife.

EXTERNAL CORROSION.

Corrosion of the outer surface of iron and steel pipe, like that which takes place on the inner surface, is the result of electro-chemical action, but differs as regards the rapidity and the extent of surface usually affected, owing to variations in the physical and chemical character of the soil in which the pipe is laid, or, when laid above ground, due to moisture and general purity of the atmosphere. When laid above ground, the pipe being more or less exposed, it permits of frequent examination and any repairs that may be found necessary to maintain it in the highest state of preservation, such work being conveniently carried out without delays or serious outlay. When the pipe is underground, the most favourable condition is that when laid in clean sandy soil, which although becoming saturated from time to time in the event of floods and heavy rain, soon becomes dry again by evaporation and good natural drainage; under these conditions, even when the soil contains objectionable soluble salts, the corrosive effects are not so likely to be of a serious nature on account of the short and intermittent periods during which corrosive action can take place. On the other hand, when the track of a pipe is through a bed of clay or other impervious soil, which owing to the natural conditions is badly drained and so remains for considerable periods in a moist or saturated

state, we may then expect to find the pipe suffering from corrosion even when the soil is free from soluble salts and the water present comparatively pure. The rate of corrosive action may also vary considerably according to the properties of the soluble salts present in the water which saturates the soil in contact with the metal of the pipe, as shown in Table No. XXIII.

TABLE XXIII.

ANALYSIS OF SOIL.

Soluble Salts in the Soil.			A. Good.	B. Bad.	C. Very Bad.
Carbonates	Calcium carbonate	$CaCO_3$	·017	·016	*·029*
	Magnesium carbonate	$MgCO_3$	—	·016	·015
	Sodium carbonate -	Na_2CO_3	—	—	—
Sulphates -	Calcium sulphate -	$CaSO_4$	·008	—	—
	Magnesium sulphate -	$MgSO_4$	·033	·003	·017
	Sodium sulphate -	Na_2SO_4	·034	·092	·138
Chlorides -	Calcium chloride -	$CaCl_2$	—	—	—
	Magnesium chloride -	$MgCl_2$	—	—	—
	Sodium chloride -	$NaCl$	·415	·083	·356
	Sodium nitrate - -	$NaNO_3$	—	—	*·039*
	Iron oxide and alumina	$Fe_2O_3 + Al_2O_3$	·012	·009	·013
	Silica - - -	SiO_2	·084	·008	·018
			·603	·227	·625
	Insoluble in water -		99·397	99·773	99·375
			100·000	100·000	100·000
	Nature of Soil - - -		Grey Sand Little Clay.	Bright Red Clay.	Buff Sandy Clay.

In the case of the 30-inch steel main for the water supply of the Western Australia Goldfield, external pitting was first noticed two and a half years after laying, when a rust hole leak occurred; on further examination pittings were found throughout the pipe necessitating the removal of the coating, scraping, and recoating at these points. Various samples of the soil and rust removed were submitted to E. S. Simpson. From these he obtained the results stated in the foregoing Table No. XXIII., showing the composition of the soil in relation to the corrosive effects produced at three different points.

The sample of soil in the third column C. corresponding to the part of pipe stated to be in a very bad condition, suggested that the increase of corrosion in this instance was due to the presence of higher percentages of calcium carbonate, sodium sulphate, sodium nitrate and sodium chloride; when the latter two are present in combination, as in this instance, they exert a strong corrosive influence. He also states the conditions favourable to corrosive action of iron and steel pipe as follows:

(1) From the action of rain water containing in solution oxygen and carbonic acid and kept mechanically in contact with the pipes and the soil. Corrosion from this cause will go on no matter what the composition of the soil, though its effect appears to be enhanced by the presence of soluble chlorides.

(2) From the presence in the soil of free acid or of pyrites which, in oxidising under the influence of moist air, liberates sulphuric acid.

(3) From the presence in the soil of soluble salts having an oxidising action on iron, principally

nitrates. These salts cannot affect the pipes when the soil is perfectly dry, but only when brought into solution by being moistened.

(4) The life of steel pipes is considerably shortened when the soil in which they are laid contains 0·1 per cent. of soluble salts, such as common salt, gypsum (calcium sulphate), etc.

The following analysis was obtained from samples of external incrustation taken from the section of piping which had suffered from corrosion when lying in contact with soil of the composition shown in Column B. in a moist condition :

ANALYSIS OF EXTERNAL RUST FORMATION.

Iron peroxide	Fe_3O_4	36·96	per cent
Iron protoxide	Fe_2O_3	6·44	,,
Lime	CaO	1·08	,,
Magnesia	MgO	·81	,,
Water below 100°		4·05	,,
Water above 100°		1·74	,,
Carbonic anhydride	CO_2	3·68	,,
Sulphuric anhydride	SO_3	·24	,,
Chlorine	Cl	·43	,,
Insoluble clay, etc.		43·80	,,
		99·23	

Comparing the above composition of external rust formation with that of the internal incrustations stated in page 115, it will be observed that the chief difference is the high percentage of insoluble clay and earthy matter present in the rust formation on the outside and the small amount of same present as sand (silica) in the rust formation inside, in which ferric oxide forms the chief constituent.

CORROSIVE EFFECTS OF STRAY CURRENTS OF ELECTRICITY.

The corrosive effects on cast-iron and steel pipes already referred to, although varying in degree, were shown generally to be the result of electro-chemical action in which local currents of electricity are set up between the adjacent electro-positive iron and the electro-negative impurities in the metal of which the pipe is constructed; corrosion of the iron being more or less active according to the impurities present and the condition of the soil around the pipe, as regards moisture and extent of the salts in solution.

Considered from that point of view alone the corrosive action may be reduced sufficiently as to be of no account when the surrounding soil is comparatively dry and free from objectionable salts referred to on page 119.

When, however, independent electric currents are taken up and conveyed along the pipe lines from some outside source in addition to those generated by local galvanic action, the rate of corrosion is correspondingly increased.

In many instances of excessive corrosion of pipes, it has been clearly shown to be the result of electrolysis due entirely to stray currents of electricity from some outside source; the development of corrosion in such examples being coincident with the introduction of an adjacent electric tramway system, in which the tramway

rails are relied upon to convey the return currents to the power stations; it has also been further observed that the rate of corrosion from this cause became more serious with developments of the tramway system and the correspondingly increased working loads throughout.

Experience has shown that the tram rails along which the electric current should have returned to the bus-bars at the electric power generating station often fail to do so efficiently owing to inherent defects in the system and inefficient methods of construction or overloading of the rails even when these are considered well bonded with copper or electrically welded together at the ends. Under such conditions part of the return current finds the line of least resistance through the intervening damp soil and along the adjacent pipe main, from which it escapes again at the other end of the system through the damp earth to the power generating station. The electric currents thus shunted from the rails are known as stray currents, which under ideal conditions should have returned along the tram rails or other specially arranged return conductor system.

These stray currents of electricity as they pass out from the tram rails through the intervening moist earth into and along the water main pipes, set up new local conditions and increased corrosive effects. The adjacent tram rail, pipe and damp soil may thus be considered as forming an immense galvanic cell, in which the pipe main and the tram rails are the electrodes, while the moist earth conducting the stray currents across forms the electrolyte.

In the illustrations Fig. XIII. referred to on page 92, the electrodes are copper and zinc, and the direction of the electric current set up within the cell is from the electro-

positive zinc to the relatively electro-negative copper. The sulphuric acid solution or electrolyte being thus broken up, the zinc dissolved, and sulphate of zinc formed, as expressed by the following equation :—The hydrogen thus formed escapes at the surface of the relatively electro-negative copper which latter is unaffected.

$$\underset{\text{Zinc}}{Zn} + \underset{\substack{\text{Sulphuric}\\ \text{Acid}}}{H_2SO_4} = \underset{\substack{\text{Sulphate}\\ \text{of Zinc}}}{ZnSO_4} + \underset{\text{Hydrogen}}{H_2}.$$

If, however, a battery of sufficient strength is inserted in the outer circuit, so that the direction of electric current is opposed to that due to the copper and zinc in the cell as shown, the copper thus becomes the anode, and is therefore the metal that goes into solution while the electrolyte is broken up, oxygen being set free at the anode and hydrogen at the kathode, as before. If, again, the battery in the outer circuit is connected up so that the electric current flows in the same direction as that set up by the cell alone, the electrolytic action and corrosive effects will now correspond to the direction of flow as before, and the rate of deterioration of the zinc is increased accordingly. For the same reason it has been found from a careful survey that the most serious corrosive effects on the pipe mains occur in those localities where the pipe is relatively electro-positive to the tram rails, and where the stray currents pass out again to the adjacent pipes, rails, or other metallic structures of lower potential.

In addition to the effects produced by stray currents from the electro-positive pipe back to the rails of a lower potential, the stray current along the pipe meets with varying resistance, particularly at the lead joints, where it continues its course by shunting round the joints through

the adjacent soil to the other side where it enters the pipe again. The corrosive effects from this shunting process have been distinctly observed to occur at the surfaces of the pipe on the side of the joints where the current leaves the pipe, while no serious corrosive effect occurs at the opposite side of the joint where it passes again into the pipe. The same shunting process also takes place between adjacent pipes and at other points throughout the length of the same pipe main, due to the varying conditions and electrical resistance of the adjacent soil throughout the pipe track.

Deterioration or rate of corrosive action varies with differences of potential, strength of current, area of surface, and length of time exposed as follows :

(*a*)	Directly proportional to the difference of potential.			
(*b*)	,,	,,	,,	strength of electric current.
(*c*)	,,	,,	,,	period of action.
(*d*)	Inversely	,,	,,	area of surface exposed.

As regards items (*a*), (*b*) and (*c*), these may be considered to represent the unavoidable electrical conditions in different localities. Item (*d*), however, varies according to the physical and chemical properties of materials of construction and the condition of the protective coating or wrapping employed.

Apart from local galvanic action due to roller scale, and other impurities, the yielding and bending action in long thin steel pipe is more likely to produce cracking and other defects in thick bituminous coatings than with the more rigid cast-iron pipe, which is itself less affected by stray currents than steel pipe, according to H. P. Brown as stated in J. N. Friend's treatise on the *Corrosion of Iron and Steel*. Defects in the coating by cracking

or otherwise correspond to so many points of restricted area throughout the surface of the pipe main where stray currents of electricity find a relatively easy path to the adjacent soil depending on the extent of surface exposed. The effects of electrolytic action and consequent corrosion of the metal being more active where the area exposed is restricted as compared with larger areas of surface where the current strength becomes correspondingly reduced or dissipated.

As an example of the serious corrosive effects of electrolytic action due to stray currents, we have the experience at Pittsburg, U.S.A., with the water and gas mains (particulars of which are given by Lanpher and Smith in their paper read before the Engineers' Society of Western Pennsylvania, 1911). The whole area included in their electrical survey was divided into sections characterized respectively as dangerous or safe districts, according to whether they were found electro-positive, *i.e.* where the direction of current was from pipes to rails, or negative, corresponding to the opposite direction of current flow.

The dangerous districts were those found to be electro-positive, and the safe were those districts found to be electro-negative. The maximum positive readings obtained were as high as twenty-one volts at points towards the end of the pipe system, but varying throughout so that at some districts the potential difference oscillated from one volt positive to one volt negative. These observations showed that the deterioration in districts of high positive potential conformed closely with the deterioration in those districts where the amperage or strength of return currents was also high, the latter amounting to 480 amperes of stray current passing direct to one of the positive districts by way of the water pipes,

in addition to 2340 amperes of earth currents passing over the water pipes to the rails near the power house.

As a result of these investigations in 1905, a scheme, known as the Return Pipe Feeder System, for mitigating the evil effects was proposed and carried out by E. E. Brownell, consulting electrical engineer. By this method the returning currents are tapped off at various points where increased resistance causes these currents to pass out from the pipes through earth to rails by means of specially formed gun-metal screwed plug terminals, the details depending on whether it was a steel or cast-iron pipe; to these terminals are connected corresponding copper electric cables run in suitable conduits to the negative bus-bars at the generating stations. By this means the current which formerly passed along the pipe and through the adjacent soil in its destructive wave-like course is conducted along these added feeders back to the negative bus-bars at the generating stations, each feeder being controlled by suitable switches, so that it would be convenient at all times to cut out any one or all of these auxiliary cables, and thus ascertain the efficiency of the whole or any part of the system. The results obtained were as follows:

At one station while the load was about 12,000 amperes and the current returning over the pipes about 4600 amperes, the positive difference of potential from pipe to rails at certain points was 1·8 volts, while the switches were closed and the additional electric cables in circuit. The following day a test was made by switching out these feeders, the positive difference of potential was found to be 24 volts, as compared to 21 volts when the preliminary survey was made previous to these alterations being carried out. Similar results were obtained through-

out the different sections treated; with further modifications as regards the exact method of linking up the various gas and water mains throughout the system, the results showed a maximum positive difference as low as ·5 volts.

The importance of such mitigation schemes is, however, not confined to gas and water pipes, as under conditions of high positive difference of potential all metallic substances underground such as steel girders, columns, etc., resting on foundations, become seriously affected by electrolytic action and resultant corrosion demanding the most careful attention in order to avoid premature decay and danger of collapse.

As indicating the extent of copper cables required by this system of return pipe feeders, one district after completion, consisted of nineteen cables leading from various points throughout the pipe mains back to the negative bus-bars of two power stations, weighing about 86,000 pounds.

By the introduction of these additional cables, it was found that the return stray current leaving the pipes in the foregoing positive district had increased from 2800 amperes previously to 5000 amperes when the return pipe feeder system was installed. As a result of this increased facility for the return stray current within the scope of the installation, the electrolytic effects on other pipes, and metallic structures adjacent but outwith the scheme of protection, were found to be seriously increased, owing to the shunting of those stray currents from the unbonded to the bonded pipes.

It was, therefore, found necessary later to include these pipes of other companies within the scope of the new scheme by bonding them also to the city water pipes already treated.

This system of return pipe feeders has so far provided satisfactory results, as no indication of extended electrolytic action has been observed since its completion on any of the pipes or other structures after careful examination. It should be noted, however, that owing to later increased station loads, the positive potential difference has increased from ·5 to 1·0 volts, so that further action may soon be necessary.

Authorities differ as regards the ultimate success of the return pipe feeder system, and some characterize it as merely tinkering with this most important problem, and suggest that the real remedy is to remove the cause of the stray currents by the introduction of the double trolley system, the initial cost of which, although greater, would ultimately give the greatest satisfaction from all points of view.

MEANS OF PROTECTION FROM CORROSION.

The protection of underground pipes from the evil effects of internal and external corrosion is a question engaging the attention of the highest chemical authorities and other experts, but while they have materially assisted in the direction of a solution of this problem by their investigations and experiments regarding the theory and general characteristics of corrosive action, the protective methods suggested are more or less efficient, but often prohibitive owing to practical difficulties and excessive outlay necessary to obtain anything like a permanent and satisfactory result.

In the ordinary course, the protective method employed for metal structures above-ground exposed to the varying atmospheric conditions of moisture, etc., is to have the surfaces scraped and coated with paint at regular intervals suggested by experience. The paints used for metallic surfaces are made up so as to obtain the highest degree of anti-corrosive properties, and usually consist of metallic oxides, mixed with boiled linseed oil medium which shall adhere to the metal surface, and form an air-tight film.

Linseed oil being of vegetable origin, consists of oxygen, hydrogen and carbon. Such medium cannot, therefore, be considered as stable when in contact with iron, even allowing that the film or coat of paint is perfectly air-

tight and impervious to moisture, as the iron combines with the oxygen and liberates free hydrogen gas, which detaches the film of paint from the surface and forms blisters throughout. Such paint can therefore only be effective and efficient for limited periods, so that the usual practice is to have the old coating of paint scraped off and recoat the newly prepared surface of the metal at regular intervals suggested from experience and according to the familiar practice adopted for the proper maintenance of iron and steel structures erected above-ground.

In the case of underground pipes and other metallic structures exposed to electrolytic action by contact with the surrounding moist earth, such periodical inspection, scraping and recoating is practically impossible, and the question seems to resolve itself into that of the relative merits of the different metals employed to resist corrosion under any particular condition to be determined beforehand.

Tar and bituminous coatings, being free from oxygen and its objectionable properties to combine with iron and form rust, are well known and constitute the principal ingredients of the most successful protective coatings proposed and adopted for the protection of underground iron and steel structures. These, however, also deteriorate through time, and, at the best, can only be considered as temporary or partial remedies against the more serious corrosive action to which such structures are exposed.

The method of application employed and usually specified or recommended by engineers, particularly for cast-iron pipes, is the comparatively simple process originally proposed and carried out by Dr. Angus Smith. This consists of a mixture of a solution of coal-tar and pitch oil raised to a temperature of from 300° to 350° Fah.

in a suitable deep tank with the necessary firing arrangements and flues for coal or gas fuel. The pipes singly or in bundles are then lowered vertically until completely submerged in the hot liquid composition, which, according to Dr. A. Smith, should be composed as follows :

Dr. A. Smith's Composition.

Coal-tar	= 112	pounds.
Tallow	= 7	,,
Quick lime (slaked)	= 10	,,
Fine rosin	= 4	,,

Coal naphtha, added until the desired coating is obtained.

In ordinary practice the coating mixture consists essentially of coal-tar and pitch oil (black naphtha) in the proportion of two of tar to one of oil (in bulk), the proper consistency being then maintained from day to day as suggested by experience. In order to produce the most satisfactory coating both inside and outside, the pipe if not previously heated should be allowed to remain in the hot solution from twenty to thirty minutes to ensure that the metal of the pipe becomes thoroughly heated throughout to the same temperature of 300° Fah. When withdrawn the pipe should remain suspended over the bath of oil so that any excess of coating material may be allowed to drain back into the tank ; the more volatile ingredients are then evaporated by the heat in the body of metal, while at the upper end the coating proper begins to set and hardens quickly. Thus a uniform coating is obtained which searches into the pores of the metal during the process, and so adheres firmly to the surface, particularly in the case of cast-iron pipe, with the further essential property of toughness which permits of the utmost freedom in handling, compared to the thicker bituminous and cloth-covered coatings which crack

and chip off readily in handling. When the metal surface coated is close-grained and smooth, as in the case of steel plates, patches of the metal surfaces are more liable to become exposed right away to corrosive action. In this respect many of the thicker bituminous coatings adopted for the protection of steel pipe are defective.

In applying Dr. A. Smith's composition some engineers specify that before dipping the pipe into the coating solution, it shall be previously heated in a stove arranged for that purpose. In some types of furnaces adopted for reheating, the process is anything but regular or uniform in its effect throughout, and in this respect might be considered objectionable. It has the advantage, however, of driving off any moisture that may have to some extent penetrated the metal.

This simple and comparatively inexpensive method of coating, although successfully applied for many years to cast-iron pipe, is obviously not found satisfactory when applied to steel, as for the latter class it is frequently specified that in addition to coating with Dr. Smith's solution, the pipe shall be wrapped or spirally wound with a broad band of jute or coarse canvas cloth previously saturated by embedding it in a hot bituminous solution to form a thick protective coating, which even if efficient is so far only applicable to the outside surface of pipe, and, as already pointed out, protection of the inside surface may in certain cases be of greater importance and even more necessary than that of the outside, owing to the highly corrosive properties of the water conveyed. Wire-netting has also been used to reinforce the bituminous coating materials. Pipes thus coated, when exposed to the action of stray currents of electricity, have been found to bear marks of corrosion corresponding to the

FIG. XX.

Facing p. 132.

Fig. XXI.

meshes of the wire-netting, also the direction of the spiral winding. The wires thus seem to reduce the protective properties of the coating by concentrating the action and corrosive effects of stray currents of electricity.

Reinforcement of the coating materials with cloth wrapping, etc., while adding to the general cohesive properties of a thick coating, is not a sufficient protection, and in the handling it is often badly damaged ; the surface of the pipe is thus laid bare to a greater or less extent throughout. The greater thickness of such coatings also increases the tendency to cracking and chipping due to the bending and greater flexibility of long steel pipes compared to that of cast-iron pipes. Apart from this, however, the various bituminous coating materials used can only afford temporary protection, being themselves affected by oxidation and other changes, so that the period during which they afford protection in some cases has been limited to a few years. In the case of the 30-inch steel pipe to Coolgardie, the coating lasted only seven years. Figs. XX. and XXI. illustrate how some reinforced bituminous coatings have deteriorated and become torn off so as to expose patches throughout the outer surface of these steel pipes to corrosive action. When such flaws are the result of defective wrapping or by chipping in the handling, if noticed before the pipe is laid, they are usually repaired by patching on the track with materials supplied for that purpose. The defects of reinforced bituminous coatings are greatly increased in the case of special pipes, bends, tees and other branch pieces, owing to the difficulty by the ordinary methods in obtaining a satisfactory wrapping throughout the irregular surfaces of such pipes.

The chief characteristics of a suitable coating for the

protection of a pipe against corrosion are, that it shall adhere perfectly to the surface and itself have no chemical action on the metal; it must also be impermeable to any electrolytic solution. Such properties, however, are impossible with the available materials, and can only be attained to a limited degree in any quality of coating. In practice so far the best results have been obtained from coating consisting of coal-tar and other bituminous compositions, care being taken to have the temperature of the solution maintained during the dipping process and the surfaces of the metal properly cleaned throughout. Special care should afterwards be taken to avoid fracture of the coating in the handling by adopting suitable cushions or buffers in all operations such as when loading, unloading and transporting, or when laying and jointing in the pipe trench.

In some cases where bituminous coatings have failed after every effort has been made to obtain the best results, it has been suggested to lay the pipe in a cradle of lime concrete, with a layer of slaked lime ½-inch thick spread all over the top. By this means further corrosive action is prevented even when the coating may be damaged and moisture finds its way to the metal surface.

In other circumstances, where the surrounding condition of the pipe track permitted, the pipe has been isolated by excavating the soil at those places where excessive corrosion takes place, the pipe in such cases being also supported out of contact with the soil by means of wooden sleepers and the sides of the trench sufficiently sloped to prevent the possibility of the earthwork sliding down and again covering the pipe.

PROTECTIVE METHODS AGAINST INTERNAL CORROSION.

Owing to the excessive corrosive effects of the water conveyed in some cases and the small margin of metal usually adopted for steel piping, the useful life of these pipes has in many instances been seriously threatened in a comparatively short time. The various protective methods of coating employed on the outside are not always suitable, and often out of the question for the inside surface of a water conduit, for obvious reasons. The result is that methods of treatment are now being suggested which, from the absence of complaint, hitherto could not have been considered necessary with cast-iron pipes. These consist of chemically treating the water conveyed in order to neutralise the active corrosive properties of the salts in solution, without at the same time introducing other objections with regard to the potable character of the water so treated. Similar means have for a long time been adopted in steam boiler practice, where the feed water used was known to have a serious influence on the rate of internal corrosion.

The following reagents have been found effective in retarding corrosion inside steam boilers.

	Per 1000 gallons of water treated.
First and best is caustic soda - - -	= ·36 pounds.
Second—carbonate of soda - - -	= ·48 ,,
Third—caustic lime (quick lime) - -	= ·63 ,,

It has been suggested by E. S. Hume that either of these substances might be added in certain cases to town water supplies in the proportions stated without rendering the water less potable, the addition of lime or a mixture of lime and caustic soda being considered preferable. The particular treatment required in each case will vary, however, according to the composition and corrosive properties of the water conveyed. The substances usually found dissolved in water vary according to the nature and composition of the soil and rocks with which it has come into contact, and to reduce or neutralize such acid solutions requires the addition of some suitable alkali.

When lime is added to water as suggested, or where the water already contains a quantity of lime from natural causes, the lime combines with the carbonic acid usually present from the dissolved air, to form carbonate of lime (calcium carbonate), which becomes deposited all over the surface, forming a thin hard scale which protects the underlying surface of metal from further corrosive action. In many cases of excessive internal corrosion the quality of water conveyed is particularly free from the presence of lime. In such cases cast-iron pipes have been employed successfully throughout. On the other hand, when the water conveyed contains considerable proportions of lime from natural causes, the same trouble from corrosion does not arise.

In ferro-concrete structures an important characteristic is that the steel reinforcement is protected throughout from corrosion by the surrounding mass of concrete.

Portland cement has also been extensively used for the protection of steel structures exposed to the corrosive effects of water, damp soil, and varying atmospheric

conditions, by coating such surfaces with a cement wash or a lining of cement mortar varying in thickness from $\frac{1}{4}$ to 2 inches thick, according to the severity of the conditions tending to corrosive action, as, for example, the practice of coating and lining the insides of steel ships with cement wash or mortar lining in certain localities, in order to protect the structural steel from excessive corrosion due to the presence of water and moist conditions generally, particularly about the bilges and lower parts of the ship.

Cement is rarely used without the addition of sand, the proportions varying from 1 of cement to 2 of sand to 2 of cement to 1 of sand, and applied in the form of grout or mortar, according to circumstances.

An important example of the use of Portland cement for the protection of steel piping is that described in the *Engineering Record*, 1911, with reference to two separate lengths of rivetted steel pipes 80 inches diameter, $\frac{5}{16}$ of an inch thick, 202 feet and 161 feet long respectively. These pipes are used to form connections at both ends of the pressure tunnel through the rock at Newton with the 60-inch diameter cast-iron pipe line which forms the greater portion of the additional distribution system for the Metropolitan Water Works of Boston. This steel pipe is encased in a concrete jacket 6 inches thick at the arch and lined inside with cement mortar 2 inches thick to protect the steel from corrosion, also to cover over the rivet heads and form a smooth surface with a corresponding increase in the carrying capacity. The strength of the concrete work is here calculated to safely resist the collapsing stresses, and, as suggested in page 50, automatic air valves are fitted on each section to avoid the possibility of additional stresses due to a vacuum formed

inside in the event of the pipe being emptied too rapidly.

In carrying out the concrete work, the greatest care was taken to properly support the steel pipe against collapse and maintain it in a true circular form, otherwise the cement lining would have become cracked and destroyed, when under the working hydraulic pressure inside, tending to correct any deformation or ellipticity due to collapse.

Special care was also taken to preserve the surfaces of the steel sections of the pipe in transit and erection by coating with cement wash, which was subsequently removed by means of sand blast, recoating with cement wash in each case before proceeding to apply the cement mortar in order to secure a perfect bond between the clean bright surfaces of the steel and the concrete both inside and outside.

The cement lining 2 inches thick was carried out in sections 14 feet long and consisted of 1 part of cement to 2 parts of sand, mixed to form grout, which was after thorough mixing conducted through two tubes 2 inches diameter, 3·5 feet apart, from barrels overhead under a 4-feet head of pressure, the displaced air between the collapsible steel forms or centering employed being allowed to escape freely through adjacent 2-inch holes and tubes on the top; the filling process being continued until the grout overflowed through these air tubes, maintaining at the same time the head of pressure during the process. To avoid air pockets forming holes on the inside surface of the concrete lining, any air entrapped during the filling process was disturbed, and thus removed by repeated hammering with mallets on the inside steel forms or centering.

In carrying out the outer casing of concrete work, precautions were taken to prevent the steel pipe from floating out of line, while the concrete was plastic or semi-fluid previous to setting. The inside bracing blocks and stays supporting the steel pipe were removed after the concrete had set for three days. In forming the inner coating or lining the specially arranged collapsible steel forms or centering were removed in sections after the cement grout had been allowed to set for twenty-four hours.

In their joint report regarding the excessive corrosion of the 30-inch steel main for the water supply of the Goldfields in Western Australia, Binnie, Deacon, Ramsay and Hehner state, after approaching the problem from the electrical and chemical point of view, that the essential cause of the corrosive action on steel or iron of all waters is due to the dissolved oxygen which they contain ; also that the corrosion of the iron can be completely stopped by the removal of the dissolved oxygen, and that this is confirmed by the absence of electrical action in thoroughly de-oxygenated water.

In their experiments they found it possible to reduce the potential of iron against platinum to zero, the dissolved oxygen being removed from the water by reagents which combined chemically with it, and those capable of reducing the hydrogen ions present normally in all natural water. Having thus decided on the cause underlying corrosive action, three methods were suggested and investigated by them for the removal of oxygen in the air dissolved in the water conveyed.

First Method. Involves one of the following processes :

(*a*) The addition of ferrous sulphate and alkali to the water (not less than one-third ($\frac{1}{3}$) of a ton of iron calculated as metal per million gallons treated).

(b) Charging the water with ferreous carbonate by filtering it after it had been carbonated, through vessels containing metallic iron. This process involves the use of one-third ($\frac{1}{3}$) ton of scrap iron and the same amount of coke in the form of carbonic acid per million gallons treated.

Second Method. By the addition of three (3) grains of *Caustic Soda* to each gallon of the water, the caustic being converted into carbonate after passing through the pipes and before delivery to the consumer.

Third Method. Has for its object the de-æration of the water by boiling, the regenerative process being used whereby the issuing water heats the entering water. By this means the normal amount of 6·5 cubic centimetres of dissolved oxygen per litre was reduced to about three cubic centimetres. By reducing the pressure and the temperature corresponding to boiling point the oxygen content of the water was reduced to 1·6 cubic centimetres per litre, with a working vacuum of 5·2 inches of mercury.

This process was further simplified by avoiding the heating of the water and maintaining as near as possible a perfect vacuum into which the water was allowed to pass in a finely divided state. At the atmospheric temperature of 62·6° Fah. experiments showed that the dissolved oxygen was reduced by this method from 6·5 to 1·4 cubic centimetres per litre of water.

By this mechanical method of treatment not only was the cost diminished, but the unpleasant chemical reagents, however harmless, were avoided.

The relative efficacy of the various methods of treatment suggested is shown in the following table derived from experiments on the rusting of bars cut from the steel

pipe referred to, the water flowing over the steel in the day time, and stationary at night, equal quantities being used for each experiment:

RESULTS OF EXPERIMENTS OBTAINED FROM SEVEN DAYS' CONTACT OF WATER AND COOLGARDIE MAIN STEEL.

TABLE XXIV.

(1) London water in ordinary air.

(2) Kalgoorlie water in ordinary air.

(3) Kalgoorlie water plus 25 per cent. more $FeSO_4 + 7H_2O$ than was necessary to combine with all free oxygen plus NaOH exactly sufficient to precipitate $Fe(OH)_2$ in pure nitrogen atmosphere.

(4) Kalgoorlie water same as regards iron; sufficient alkali to leave 3 grains per gallon free NaOH; nitrogen atmosphere; precipitated ferrous hydroxide removed by filtration.

(5) Kalgoorlie water same as No. 4, precipitate not removed.

(6) Kalgoorlie water with ferrous sulphate only; same amount as above; nitrogen atmosphere.

(7) Kalgoorlie water with 3 grains of caustic soda per gallon only; nitrogen atmosphere, but water containing its own dissolved oxygen.

(8) Kalgoorlie water used was that which had been sprayed into a vacuum of ¾ inch mercury; nitrogen atmosphere.

Bar.	Weight in grammes.	Surface sq. m.m.	Loss of Weight.	Loss for one sq. centimetre.
1	13·6750	1308	·0225	1·72 milligrammes.
2	26·0930	2014	·0480	2·38 ,,
3	28·0830	2241	·0033	·15 ,,
4	29·3411	2279	·0005	·02 ,,
5	28·5822	2244	·0012	·05 ,,
6	23·3650	2026	·0050	·24 ,,
7	29·0885	2229	·0040	·16 ,,
8	24·2560	2110	·0033	·15 ,,

The final conclusion arrived at by these distinguished authorities in this country, who were called upon to advise the Western Australian Government, is that the most economical method for arresting the excessive corrosion taking place in the 350 miles of 30-inch steel conduit would be to remove the contained air by spraying the water conveyed into a vacuum and to add to it about three grains of lime per gallon, which quantity may possibly be reduced if the water when delivered is found to be alkaline, and in addition they submitted a design of the apparatus proposed capable of de-ærating one million gallons of water per day (subject to modifications).

The disastrous results experienced with the steel main referred to are an object lesson of the necessity for thorough investigation into the nature of the soil and quality of the water to be conveyed before proceeding with such important undertakings, as the enormous cost of remediable methods, even if successful in checking the destructive corrosion as in this case, may far outweigh the extra initial cost of less attractive but more efficient and satisfactory materials of construction for the special conditions under consideration.

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